Columbia University in the City of New York

LAMONT GEOLOGICAL OBSERVATORY
PALISADES, NEW YORK

STUDIES ON THE DEEP CIRCULATION IN THE ANTILLEAN-CARIBBEAN BASINS

by

Georg Wüst
Emeritus Professor
Kiel University
Kiel, West Germany

and
Visiting Professor
Columbia University
New York

TECHNICAL REPORT NO. CU-1-62
Contract AT(30-1) 2663

October, 1962

STUDIES ON THE DEEP CIRCULATION

IN THE

ANTILLEAN-CARIBBEAN BASINS

by

Georg Wüst
Emeritus Professor
Kiel University
Kiel, West Germany

and
Visiting Professor
Columbia University
New York

TECHNICAL REPORT NO. CU-1-62
Contract AT(30-1) 2663

October, 1962

STUDIES ON THE DEEP CIRCULATION
IN THE
ANTILLEAN-CARIBBEAN BASINS

by
Georg Wust

Since 1961 the author has been working, with some assistants, at Lamont Geological Observatory, on the deep circulation of the water masses in the basins of the Antillean-Caribbean region. The results of this study will be published in a monograph now in preparation. With the help of the largely increased observation material, this monograph will continue the comprehensive studies of Parr and Dietrich in 1937-1939 on the same region. Our work is based on all available data, i.e., approximately 2,000 hydrographic stations, from which about 1,200 reach deeper than 1,000 meters, and on additional observations such as thermal gradient measurements and geochemical determinations in the depth. Also, the newest conceptions of the bathymetrical conditions are, in collaboration with Dr. Bruce Heezen and Marie Tharp, taken into consideration. With regard to the oceanographic serial measurements of temperature and salinity, Woods Hole Oceanographic Institution has made the greatest contribution to the source material, not only in quantity but in quality. Between 1932 and 1961 the Woods Hole research vessels, ATLANTIS, CARYN, CRAWFORD, and ALBATROSS, have made about 30 oceanographic cruises through the Antillean-Caribbean region.* Continuous inspiration and help in our studies have come from Dr. Maurice Ewing. Since 1955 he has

* The author is very grateful to Dr. Fey for permission to use, in this study, Joe Barrett's unpublished data of the ATLANTIS Cruise 1961.

organized seven mainly geophysical cruises of VEMA through the Antillean-Caribbean Sea, which, in crucial regions have contributed to our study new precision depth recordings, thermal gradient measurements in the near-bottom layers, and a number of hydrographic stations in connection with geochemical measurements. In the collection of the source material and the analysis of the mass of data, the author enjoyed the continuous assistance, in the oceanographic laboratory at Lamont Observatory, of Robert Gerard, Arnold Gordon and Robert Sexton. In this paper only an abstract of the new conceptions on the circulation in the cold water sphere can be presented, based mainly on the "core layer method," which, in connection with T/S relationship and sections along the axis of the deep currents, has proved successful in such studies. Further chapters on the circulation in the warm water sphere and on the volume transports through selected cross sections are still in preparation. Such is the case with the chapter on the results of the C^{14} and tritium methods for the geochemical estimation of the age of the water masses, which will be contributed by Maurice Ewing, Wallace Broecker, and Robert Gerard.

In spite of some similarities in their intercontinental situation, their depths and basin-ridge structure, the "American Mediterranean Sea" and the "European Mediterranean Sea" show remarkable differences in the renewal of their water masses. The deep circulation of the former takes place in a cold water sphere of 3° to 7°C and of salinities less than 35 o/oo; its deep and bottom waters are formed far outside the basins at the surface of

[illegible]

[illegible]

the subpolar regions in the open Atlantic Ocean. In the"European Mediterranean Sea," however, the deep circulation takes place in a deep-reaching warm water sphere of more than 13°C and very high salinities of 38 to 39 o/oo. Its deep and bottom waters are formed inside the basins at the surface of their northern border regions. These differences in the circulation processes are mainly caused by the dissimilar degree of isolation, i.e., by the sill depths and dimensions in their oceanic passages as well as by the differences between the climatic conditions. Therefore, the author prefers to replace the name "American Mediterranean Sea" introduced by Krümmel (1907) and used by Dietrich (1939) and Sverdrup (1942), with the more appropriate nomenclature "Central American Sea," which consists of the"Antillean-Caribbean Sea"and the"Gulf of Mexico." The latter has been omitted in our study.

The generalized bathymetrical map (Figure 1) is based on the available bathymetric source material and in some critical regions also on the distribution of the potential bottom temperature. By the hatching of the depths smaller than 2,000 meters, it gives a clear picture of the basin-ridge structure and the nomenclature used. With regard to the ridges, it shows some new conceptions of the gaps and sill depths in the Outer Ridge, the Cayman Ridge, the Aves Ridge, and in the Beata ridge, as well as in the Antillean Arc (Windward Passage, Anegada and Virgin Isls. passages. Dominica Passage). These sill depths have a decisive influence on the water renewal in the interior basins.

Mexico Basin
Yucatan Basin
Cayman Ridge
Cayman Trench
Cayman Basin
Jamaica Ridge
Hispaniola Basin
North America Basin
Outer Ridge
Puerto Rico Trench
Venezuela Basin
Colombia Basin
Aruba Gap
Aves Ridge
Antillean Arc
Grenada Basin
Tobago Basin
Barbados Basin
85°
80°
75°
70°
65°
60°
25°
20°
15°
10°
Basins and Ridges of the Caribbean-Antillean Region
Generalized Contour lines for 1000m, 2000m, 3000m, 4000m, 6000m, and 8000m (in special areas for 5000m, and 5500m), all Given in Hectometers
The Symbols Concern the Near Bottom Observations of Temp and Salinity
<2000m

FIGURE 1

In the cold water sphere of the Antillean-Caribbean basins, we have four core layers in which the spreading and mixing processes of the intermediate, deep and bottom water masses can best be studied:

1. The core of the Subantarctic Intermediate Water characterized by the intermediate salinity minimum in regionally various depths between 700 and 850 meters.

2. The core of the North Atlantic Water characterized by the upper intermediate maximum of oxygen in various depths between 2000 and 2500 meters.

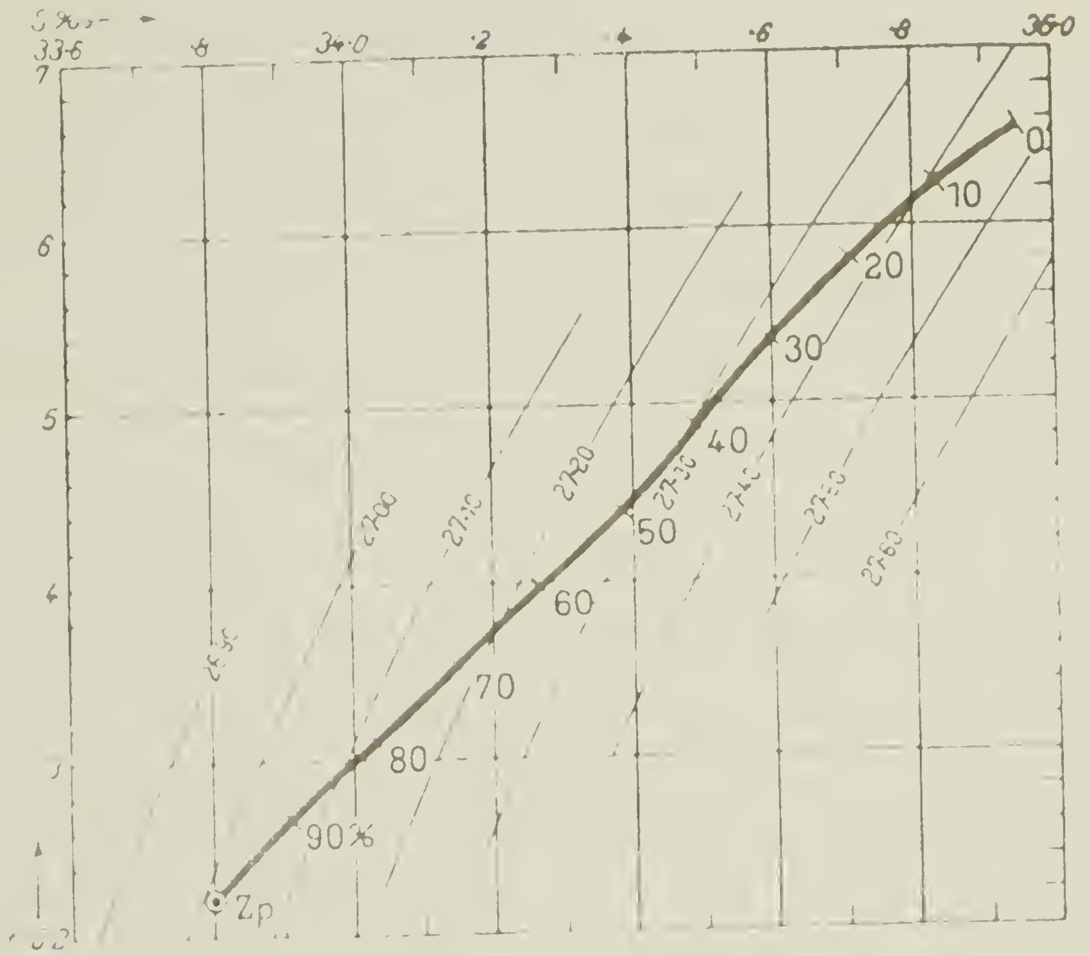
3 and
4. The cores of the Caribbean Bottom Water (inside the Antillean Arc) and the Antarctic Bottom Water (outside) characterized by the potential temperature and salinity in the near-bottom layers.

Figure 2 demonstrates the spreading of the Subantarctic Intermediate Water towards the north along the core of the salinity minimum in the open Atlantic south of 20°N (Wüst, 1936). After sinking at the southern polar front, the core of this water type north of 40°S lies in the whole breadth of the ocean at depths between 700 and 900 meters. North of 30°S we find more and more an intensification of the northward spreading on the western side, obviously as an effect of the Coriolis force. Therefore, close to the South American continental slope, we can speak of a Subantarctic Intermediate Current. This is proved by Defant's dynamic calculations which, on the west side of the ocean, indicate velocities between 6 and 12 centimeters per second (Defant, 1941). In the central and eastern parts of the South Atlantic, there are no measurable currents, but turbulent and lateral diffusion processes which maintain the intermediate salinity minimum. It is surprising

Salinity ($^0/_{00}$) and depth (metres) of the core layer of the subantarctic intermediate water in the Atlantic (according to Wüst).

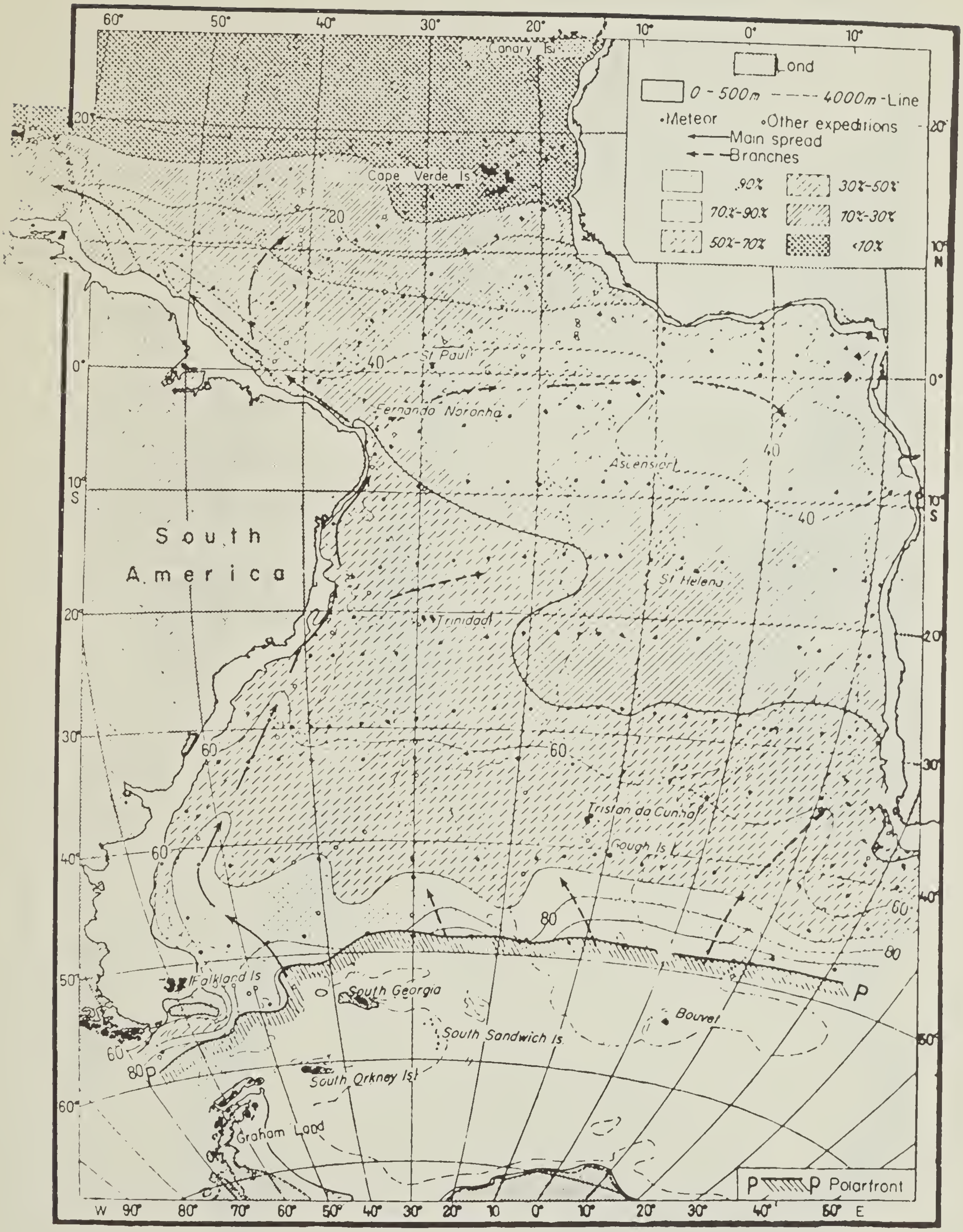
FIGURE 2

that north of the equator the axis of the main spreading persists on the western side and does not shift to the east, which would correspond to the opposite sign of the Coriolis force. In these regions the deeply-penetrating gradient forces of the mainly wind-driven Guiana-Antillean and Caribbean Current Systems evidently extend their influences upon the further spreading of the Subantarctic Intermediate Water in 700 to 850 meters depth to the northwest and west. Its final well-defined admixtures are found at the Yucatan Straits in 22°N as is shown later. With the help of the T/S correlation, a standard curve was constructed by the author (1936) for the entire area where this water type is found (Figure 3). From this curve the percentage amounts of the Subantarctic component for all stations south of 19°N was derived. In this way, the spreading of the Subantarctic Intermediate Water could be represented by contour lines of equal percentage content of this water type. Its main axis and branches are shown by arrows (Figure 4). In 8° to 12°N outside the Antillean Arc we find the subantarctic component to be 30 to 35%. For the Antillean-Caribbean basins, where in 1936 only eight marginal stations could be utilized, there are now about 540 stations at our disposal. Figure 5 shows for these basins the new picture of the spreading within the Subantarctic core layer in 700 to 850 meters. The main inflow of this water type with salinities of less than 34.70 o/oo takes place through the two passages on both sides of St. Lucia Island. These two tongues later combine and cross the central regions of the Venezuela, Colombia, Cayman and Yucatan basins along an axis,



Standard curve of the [TS]-relationship for the entire area of the core layer of the subantarctic intermediate water in the Atlantic.

FIGURE 3



Spreading of the subantarctic intermediate water represented by lines of equal percentage content of this water type (according to Wüst). The full arrows indicate the main course of the water spreading and the dashed arrows indicate the (more turbulent) side branches of it.

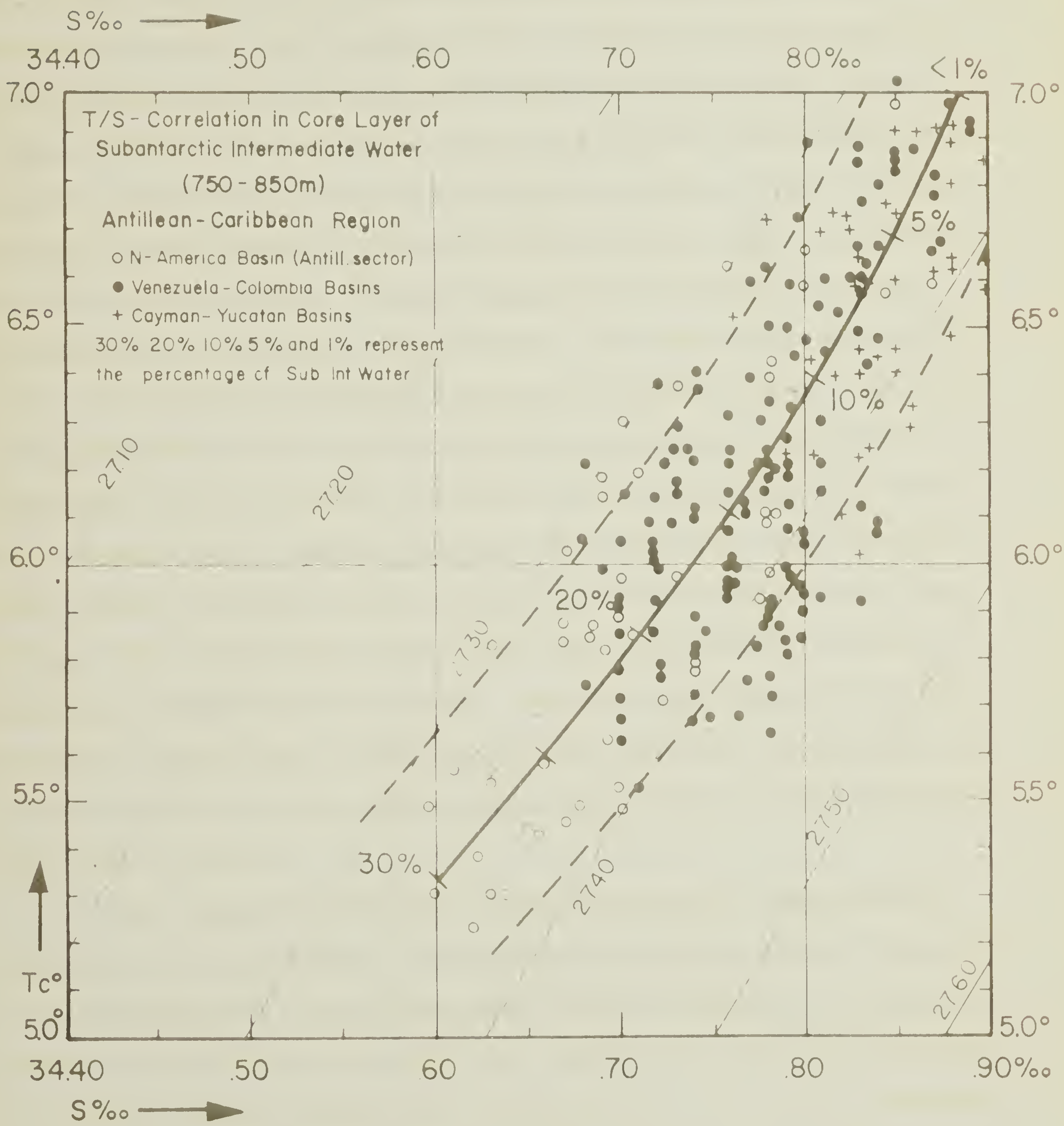
FIGURE 4


Spreading of the Subantarctic Intermediate Water within its core (Intermediate Salinity Minimum) in 700-850 meter depth
0-500m
<34.60
34.60-70
34.70-80
MAIN SPREADING
FOR EXPLANATION OF SYMBOLS SEE TABLE I
No Well Defined Minimum
85°
80°
75°
70°
65°
60°
25°
20°
15°
10°
34.86 - 34.88
<34.85
34.86 - 34.89
>34.85
34.85
34.80
34.75
34.70
34.65
34.60
34.67-34.69
34.71 - 34.74
34.76 - 34.80
<34.60

FIGURE 5

which coincides with the axis of the strongest surface currents of 1 to 1.5 miles per hour (or 50 to 80 cm/sec) on the average. The contour line of 34.85 o/oo characterizes the last well-defined admixtures of the Subantarctic water. Outisde of this isohaline, only spurious traces of this water type are to be found with values between 34.86 to 34.89, as in the Gulf of Mexico, Straits of Florida and north of the great Antillean islands. This is proved by the T/S correlation (Figure 6) which presents some corrections of our former diagram. The new observations disclose a modest spreading of the points. About 88% of them show deviations of less than ± 0.05 o/oo (in salinity) from the standard curve. The point S = 34.85 o/oo on the curve represents a percentage amount of 5. Therefore, it is reasonable to put at this salinity the limit for the construction of contour lines in the core map. The standard curve shows relatively small deviations from the density line of 27.36. This corresponds to the idea that in this area a slow isentropic advection takes place. Here the spreading of the Subantarctic Intermediate Water in its axis has lower velocities than along the South American continental slope south of 10°N, probably less than 5 cm/sec.

The vertical structure of the Subantarctic Intermediate Water and its dependency on the increasing mixing effects are clearly demonstrated by the longitudinal section (Figure 7), representing the stratification in salinity, temperature and oxygen between 0 and 2000 m along the axis of its spreading. This most characteristic chief longitudinal section begins outside the Antillean Arc 200 miles southeast of the Barbados and follows over a distance of



S‰ →
34.40
.50
.60
70
80‰
<1%
7.0°
6.5°
6.0°
5.5°
5.0°
T/S - Correlation in Core Layer of
Subantarctic Intermediate Water
(750 - 850m)
Antillean - Caribbean Region
○ N-America Basin (Antill. sector)
● Venezuela - Colombia Basins
+ Cayman - Yucatan Basins
30% 20% 10% 5% and 1% represent
the percentage of Sub Int Water
5%
10%
20%
30%
2710
2720
2730
2740
2750
2760
Tc°
34.40
.50
.60
.70
.80
.90‰
S‰ →

FIGURE 6

2250 miles (or 4200 km) the main axis of the Subantarctic Intermediate Current. This axis coincides approximately also with the axis of the Subtropical Undercurrent in 75 to 150 m depth, where after Pillsbury's direct current measurements in the passages (1885-1889) we may assume mean velocities between 40 and 60 cm/sec (Model, 1930). Our section crosses the Antillean Arc through the south St. Lucia Passage and the south Venezuela and the central Colombia basins from east to west. From here it turns to northwest by crossing the western Jamaica Passage and the west Cayman and Yucatan basins. Ninety per cent of the serial measurements used in our section were accomplished by Woods Hole ships during the winter months and in the following periods (from left to right): 1933-1935, 1954-1958, 1937-1938 and 1952. In parenthesis: There is in the Antillean-Caribbean Region a remarkable dependency of the oceanographic activity on the season which has unfortunately prevented the author from studying also the interesting summer conditions. Because of the shifting of the thermal equator in mid and late summer to the Caribbean Seas, we find here in this season low salinities (less than 35 o/oo) the highest tropical temperatures (29°C) at the surface and much rain (about 100 mm/month), on the whole not so pleasant conditions as in the normal travel season preferred up to now by the American oceanographers. But it would be a promising task to fill this gap by future systematic summer cruises.

LONGITUDINAL SECTION ALONG AXIS OF SUBANTARCTIC INTERMEDIATE CURRENT

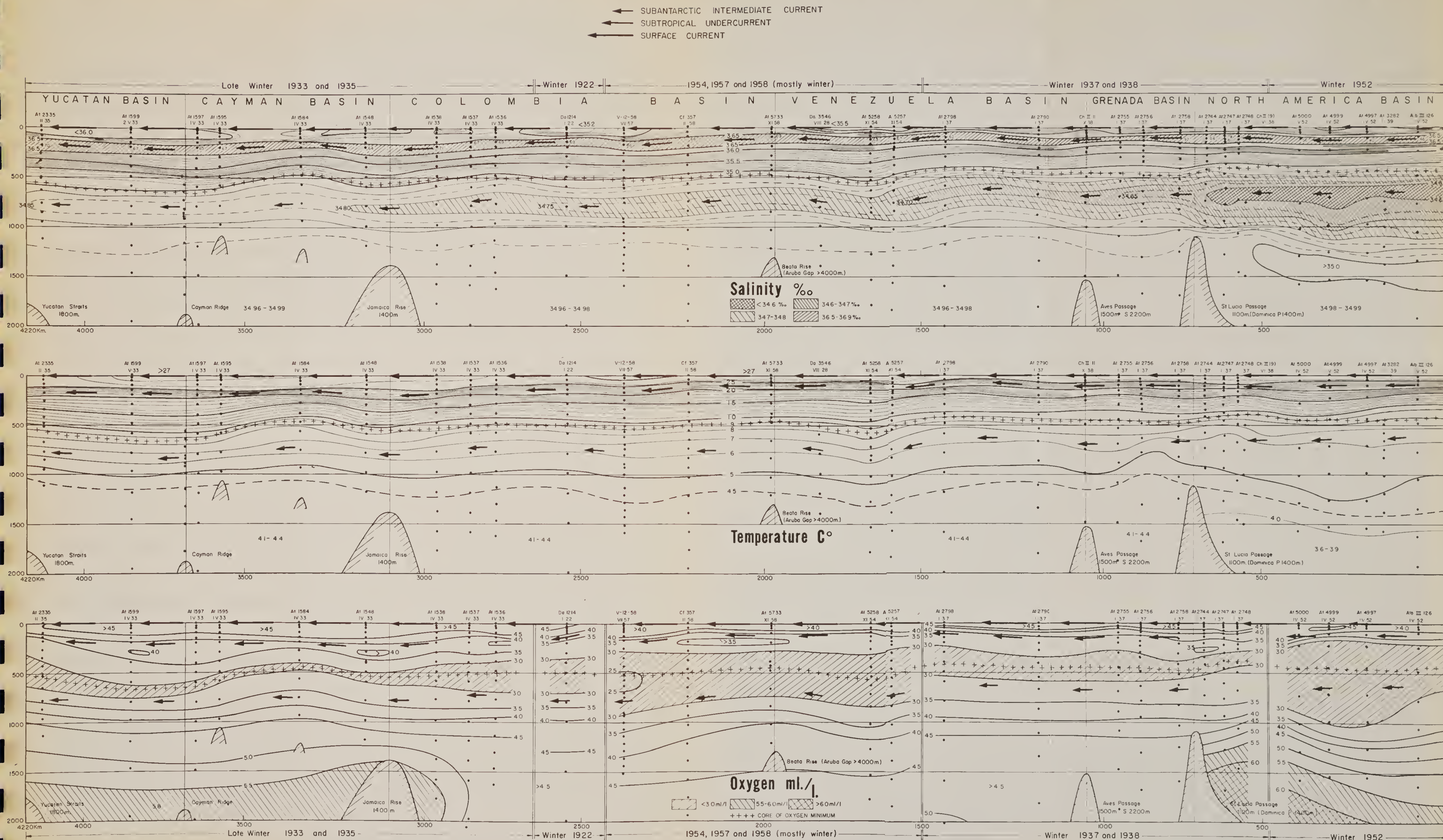


FIGURE 7

The salinity section shows clearly by the hatching the tongue-like spreading of the Subantarctic Water between 500 and 1000 m, its increasing salinity and decreasing vertical extent from E to W and NW. This pattern is mainly a consequence of the turbulent vertical exchange coefficients, which Defant (1936) computed as 5-10g cm sec^{-1}. Quite different conditions exist in the Subtropical Undercurrent which in depths between 75 and 200m is characterized by the intermediate salinity maximum of more than 36.5 o/oo (the small hatched ribbon in our section). Contrary to the Subantarctic Intermediate Current, there is in the Subtropical Undercurrent,over a stretch of 4200 km, no continuous change in salinity and thickness of the core layer. Why? In 1936 and 1939 the answers were given by Defant and Montgomery with regard to the similar conditions of this Undercurrent in the open Atlantic. In both cases the average thickness of the core is only 50 to 75m. The comparison of the salinity section with the temperature section shows that the salinity maximum coincides with the very steep thermocline and because of the corresponding salinity inversion also with the strongest vertical gradient in the density field, the very steep pycnocline. The spreading of this subtropical intermediate water type is caused by advection and turbulent diffusion. But because of the high stability of the stratification within the pycnocline, the effect of the latter process is strongly restricted so that the horizontal spreading in our section seems to take the character of a laminar flow. This has been confirmed by Montgomery who found the coefficient of vertical eddy diffusivity as only

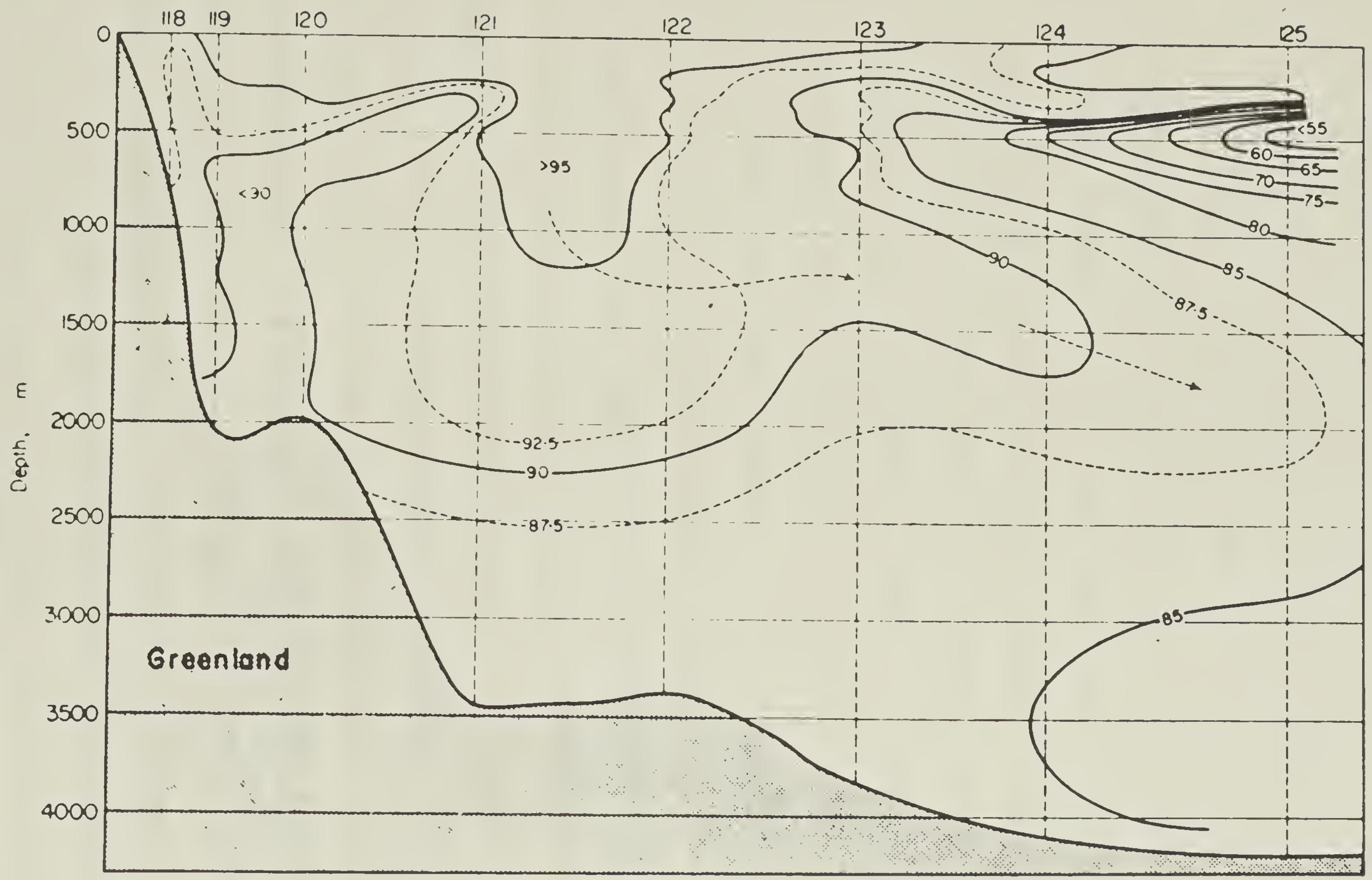
0.4g cm sec^{-1}. By including the effects of lateral mixing, Defant (1962) has estimated that the turbulent diffusion coefficient cannot be far from the molecular diffusion coefficient for salt in water (0.011).

Whereas in the longitudinal sections of salinity and temperature, the serial measurements of the various cruises match well together; contrary is the case in the oxygen section. The oxygen determinations of the various periods of years are obviously not comparable. By the hatching of the intermediate oxygen minimum ($<$ 3 ml/l) and of the intermediate oxygen maximum ($>$ 5.5 respectively 6.0 ml/l), we have demonstrated the inhomogeneity of the observations. The oxygen values determined on Woods Hole ships between 1954 and 1958 (and also by VEMA) are in the whole water column on the average 10% lower than the values of DANA in 1922 and of ATLANTIS in 1933-1935, 1937-1938, and (only in the deep water) of ATLANTIS in 1952. The question arises whether in the period 1954-1958 mainly systematic errors in the titrations have contributed to these anomalies, as recently Dr. Carritt has assumed, a question to which we later return. In any case, we must divide our longitudinal section in five parts, each of them valid only for the special period of years.

With regard to the depth of the core within the oxygen minimum, the five parts agree fairly well. This core coincides with the isotherms of 8° and 9° and with the isohalines of 34.9 and 35.0 o/oo (as is shown by the line of black crosses). In other words, the boundary between the warm water and the cold water sphere is here

(as in the open Atlantic) best characterized by the core of the intermediate oxygen minimum. This boundary also coincides with the upper boundary layer of the Subantarctic Intermediate Water. But it cannot be explained by a lack of sufficient renewal of the water masses, i.e., by dynamical reasons and cannot be regarded as a layer of very slow advection. Here the strong currents reach deeper than the oxygen minimum in the adjoining parts of the open Atlantic, from where it is transported with them to the Antillean-Caribbean basins (Wyrtki,1962). The dynamic boundary layer, i.e., the reference layer (or layer of no motion) for dynamic computations is inside of the Antillean Arc to be sought in depths below the Subantarctic Intermediate water, i.e., probably in an inclined surface between 900 and 1200 m, when we transfer Defant's oceanographical (dynamic) triangulation method (1941) from the open Atlantic to the Caribbean basins.

The next core layer concerns the spreading of the North Atlantic Deep Water, which is formed above the submarine slopes of South Greenland. It is well known that here during February-March, small scale convection and deep-reaching inclined advection of heavy and high oxygen water masses take place. This was clearly shown for the first time by Wattenberg's oxygen winter section in 1938 (Figure 8). These processes give rise to the North Atlantic Deep Current between 2000 and 2500m, which is characterized by the upper intermediate oxygen maximum (greater than 6.0 m l/l). By the influence of the Coriolis force, this southward flow as a permanent feature of the deep circulation is most developed as a boundary

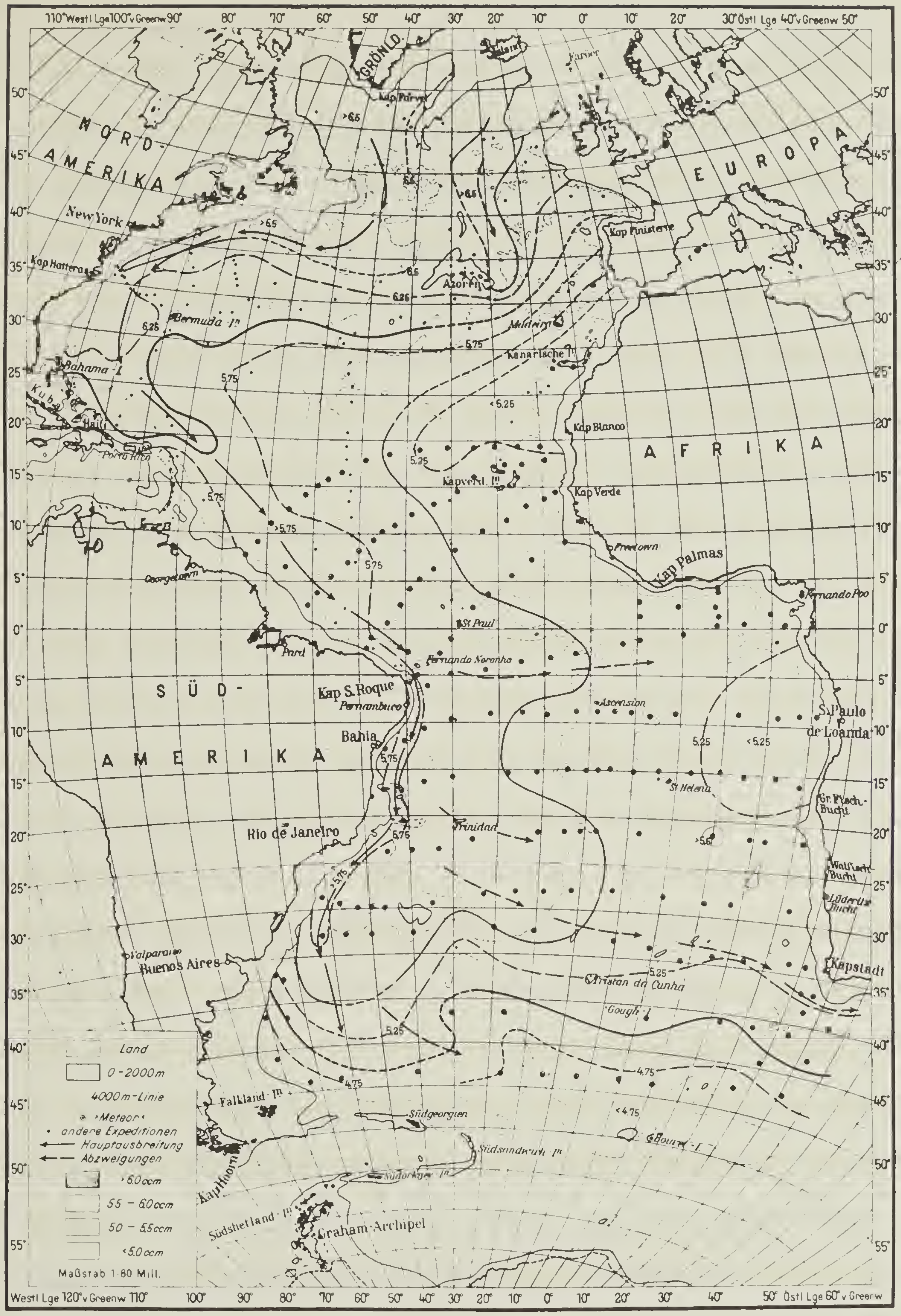


Distribution of oxygen (in percentage) in a section from the southern tip of Greenland to the Great Banks of Newfoundland (according to Wattenberg).

FIGURE 8

current along the western continental slope of the North Atlantic (Figure 9). This core map, published by the author in 1936, is mainly based on the oxygen determinations of 187 METEOR and 63 ATLANTIS stations, which match sufficiently well together. Forty-seven stations of four other research vessels (DANA, ARMAUER HANSEN, DISCOVERY and MARGRETHE) were also used. The titrations of the DISCOVERY II Expedition 1931 between 50°S and 15°N have, on the average, systematically given 4% lower values than the other observations. Corresponding to the dynamic computations of Defant (1941) and of the author (Wüst, 1957) and to the recent direct current measurements of Swallow-Worthington (1961), the velocities of this deep current (which in the North Atlantic can be called a counter current below the Gulf Stream System and also below the Antillean-Guiana Current System) are in the range of 6 to 18 centimeters per second. In other words, in the current axis it would take between 3.8 and 1.3 years to transport the water masses over the 4000 miles from the source region south of Greenland to the region along the Antillean Arc. When we consider the vertical and horizontal extension of the core of more than 6.0 ml/l, then probably we would have to reduce the mean velocity to three centimeters per second and to enlarge this time factor to an upper limit of 7.6 years.

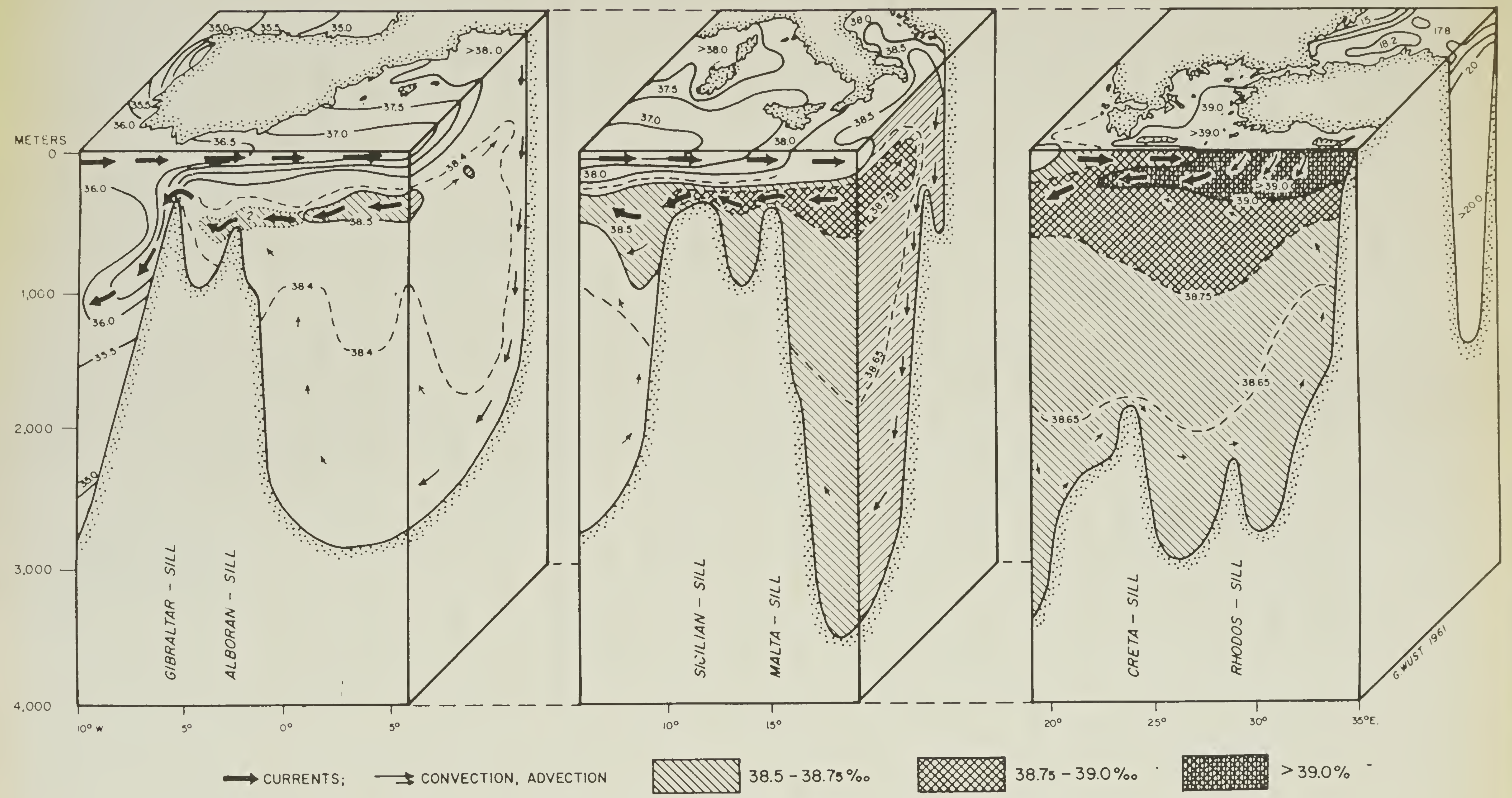
Let us take a look at the origin and the spreading of the deep water in the Mediterranean Sea, which is also characterized by an intermediate oxygen maximum in 1500 to 2500 meters but with lower values (between 3.8 and 4.6 ml/l) as in the Atlantic. The



Sauerstoffgehalt (ccm) der Kernschicht (intermediäres Sauerstoffmaximum) des mittleren nordatlantischen Tiefenwassers

FIGURE 9

schematic block diagram of the Mediterranean deep circulation Figure 10 demonstrates that the deep and bottom waters here are formed during winter inside the basins at the surface of the most northern border regions of the Balearic basin and in the Adriatic Sea. These relatively cool, heavy and high oxygen water masses sink at first vertically by small-scale convection in shallower depths. Then they slide by inclined advection (in the case of the Otranto sill, by occasional overflow) along the continental slope to depths of more than 2000 meters where they spread southward and eastward by slow advective flow. This flow is clearly shown by the oxygen distribution in the core layer in 1500 to 3000 meters in which the available 120 oxygen values of nine expeditions (THOR 1908-1910, NAJADE 1910-1914, DANA 1928 and 1930, ATLANTIS 1948 and 1958) could be used as if observed synoptically (Figure 11). Quite different and apparently highly variable conditions exist in the oxygen distribution of the Antillean-Caribbean basins. Here we could utilize for the circulation studies the oxygen determinations of eight research vessels taken at approximately 350 stations in 12 various years between 1921 and 1961. In this period the oxygen values of the different expeditions fluctuate outside and partly also inside the Antillean Arc in an amazing extent, namely in the order of magnitude of 0.5 to 0.9 ml/l, i.e., of 9 to 17%. Therefore, contrary to the Mediterranean Sea, here special core maps must be constructed for each year or couple of years in which the particular oxygen determinations are made.



Schematic block diagram of vertical circulation and distribution of salinity in the Mediterranean Sea during winter.

FIGURE 1 0

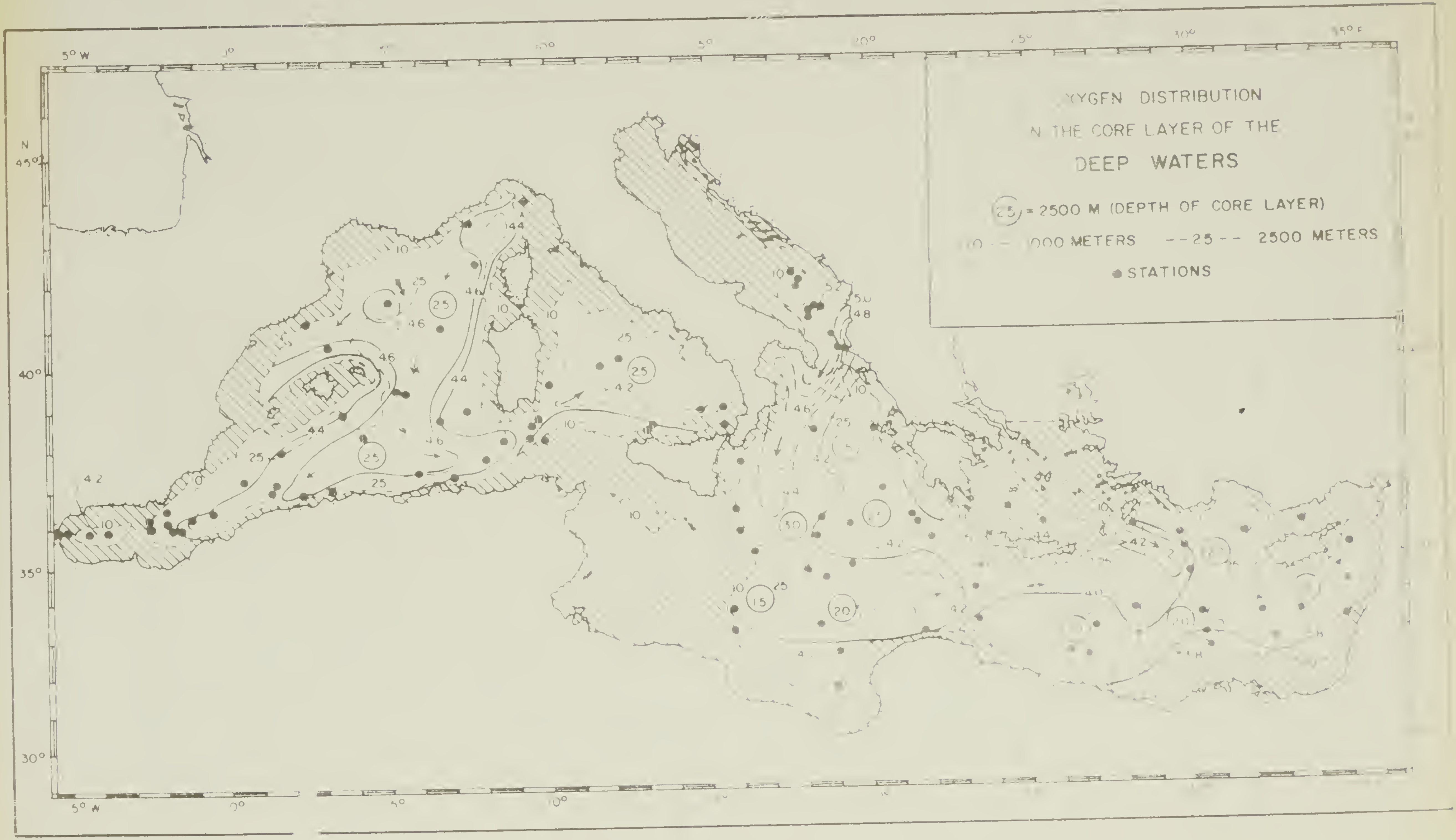

XYGEN DISTRIBUTION
N THE CORE LAYER OF THE
DEEP WATERS
25 = 2500 M (DEPTH OF CORE LAYER)
10 - - 1000 METERS - - 25 - - 2500 METERS
STATIONS
5° W
40°
35°
30°

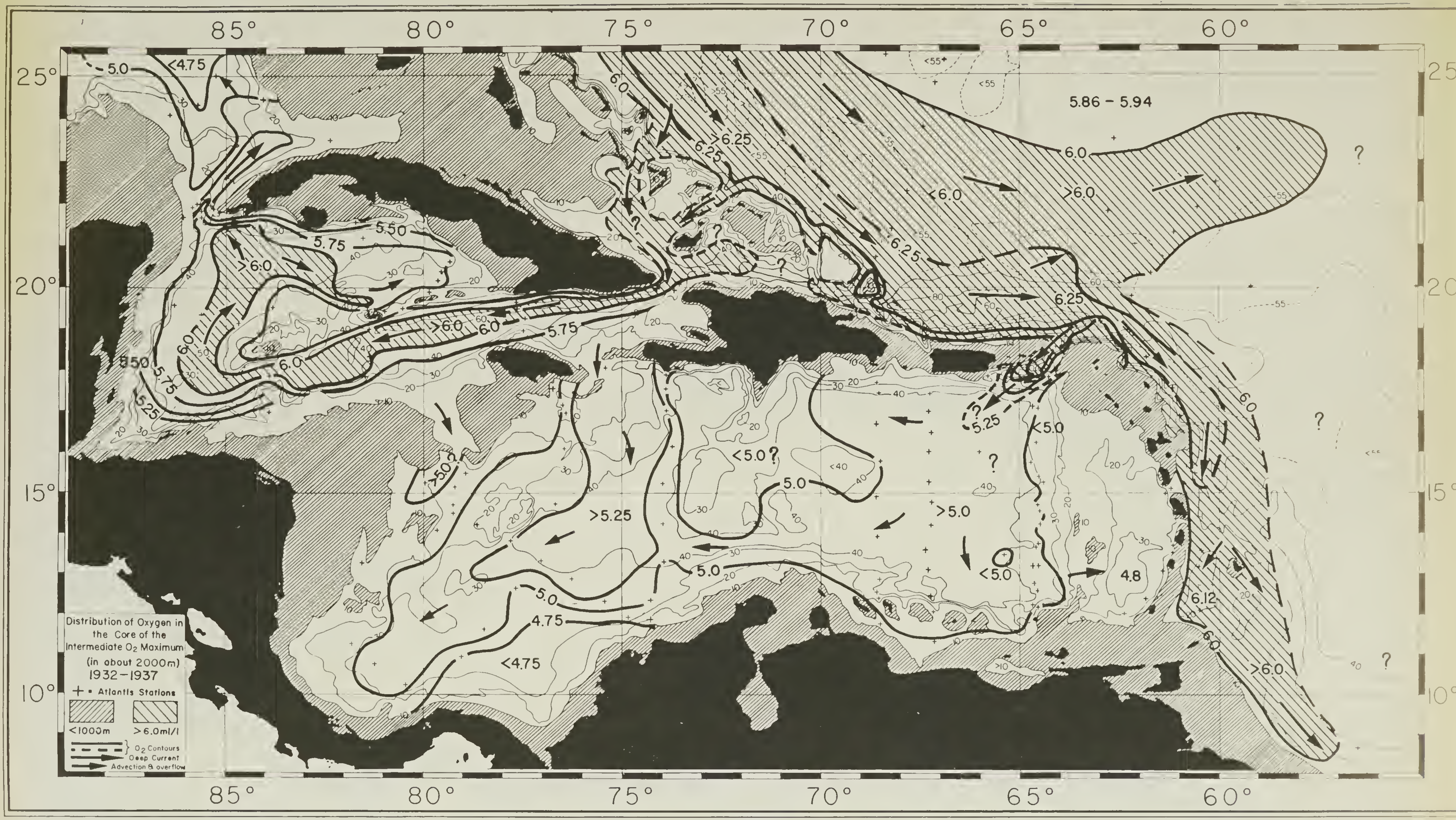
FIGURE 1 1

These variations can be the consequence of the periodic and unperiodic changes of the climatic conditions in the source region and of the circulation pattern as well as of the additional biochemical processes such as decomposition of organic matter in the open Atlantic. In his comprehensive review on "Oxygen in the Ocean," Richards (1957) has shown that its distribution is ".... the manifestation of processes which (1) add oxygen to the surface layers, (2) consume oxygen by respiratory, chemical and enzymatic oxidation, and (3) distribute it to all depths." Therefore, its distribution differs from that of the conservative properties such as temperature, salinity and density, which, in the oceanic cold water sphere, show quasi-stationary conditions, i.e., in a far-reaching approach a delicate and permanent balance between the opposite effects of advection and turbulent diffusion.

On the other hand, the possibility of systematic differences between the deep water oxygen determinations of various expeditions must be considered. Therefore, the question arises as to how much the previously mentioned methodical errors in the oxygen determinations by the Winkler method can be due to the state of the water sampler (uncoated or coated) and to the analytic difficulties. Normally the oxygen values are published to 0.01 ml/l, but the second decimal is doubtful. In 1933 Wattenberg estimated that from the methodical points of view the total error of good titrations is between ±0.05 and ±0.10 ml/l, i.e., 1 to 2 per cent, which at that time was sufficient for oceanographic purposes. Water samples taken from uncoated water bottles probably give values which are too

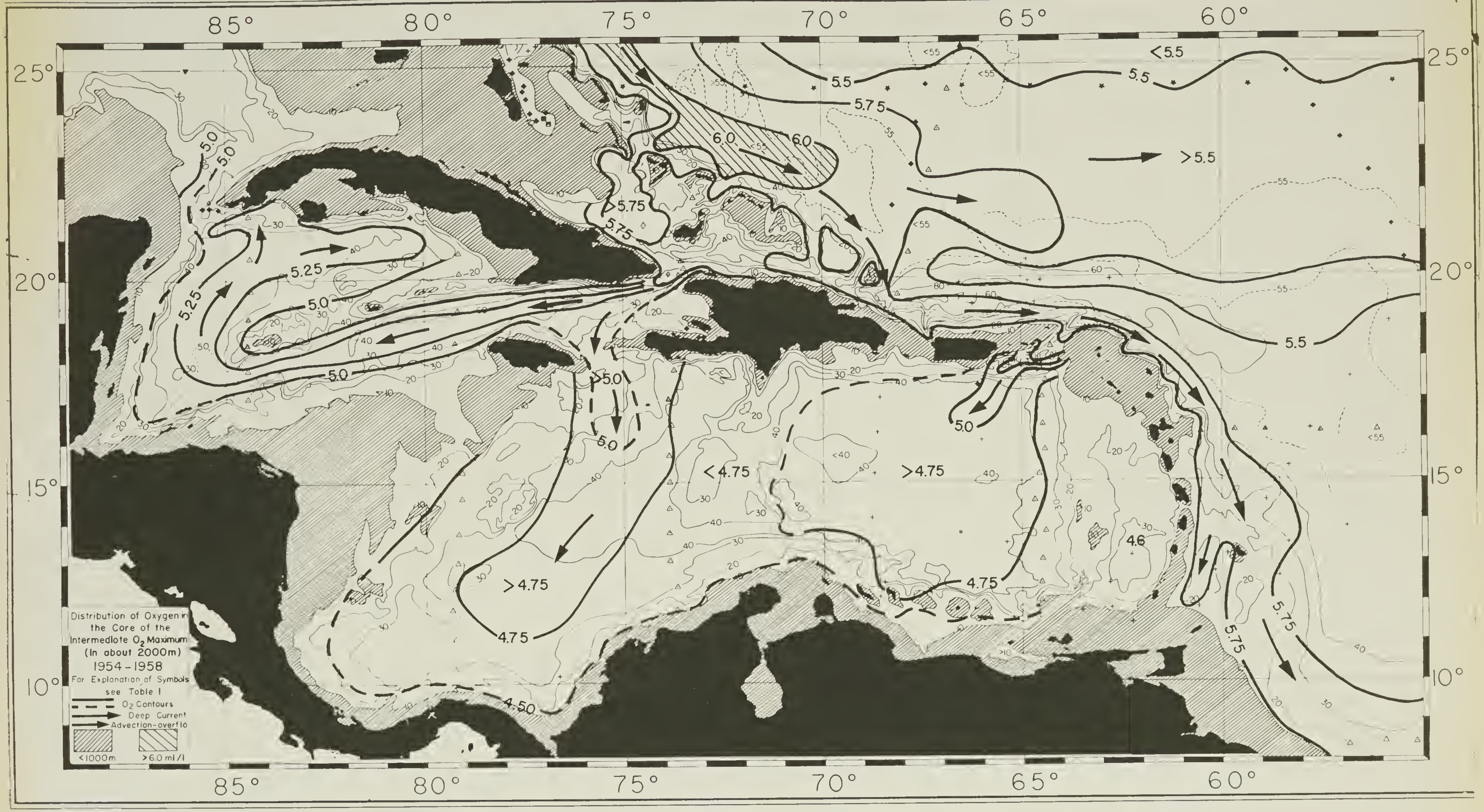
low by about 1%. But, contrary to Richards, who in 1957 called the Winkler method "still adequate, sensitive, accurate and of rugged reliability," Carritt, et al. recently became aware of occasional larger systematic errors on some former expeditions because of the different procedures used for standardizing the titer-solution. In a letter Dr. Carritt informed the author about some results of his unpublished study of the Winkler method, which shows that "...one well-published procedure gave results which were on the average 10 per cent too low." This is a little smaller than (but not too far from) the average fluctuations found by the author in the oxygen data within some basins inside and outside the Antillean Arc. By a comparative study, we have tried to test the reliability of the oxygen data observed by the various research vessels during the same year (or a couple of years). This can be done with the help of the oxygen-salinity relation. In this way it is possible to eliminate a number of doubtful values. On the other hand, the determinations of a number of research vessels made during the same period (of one to two years) in these areas do not exhibit in such diagrams suspicious, large systematic differences among their oxygen data. Therefore, we may assume that in the same period the oxygen determinations of the different ships are comparable, but probably only because they were made in the same analytic way (particularly during the period of 1954-1958).

The two maps in Figures 12 and 13 demonstrate for two distinct periods (1932-1937 and 1954-1958) the oxygen distribution in the Antillean-Caribbean basins as observed by various expeditions



Distribution of Oxygen in the Core of the Intermediate O_2 Maximum (in about 2000m) 1932–1937
+ • Atlantis Stations
<1000m
>6.0ml/l
O_2 Contours
Deep Current
Advection & overflow
5.86 – 5.94

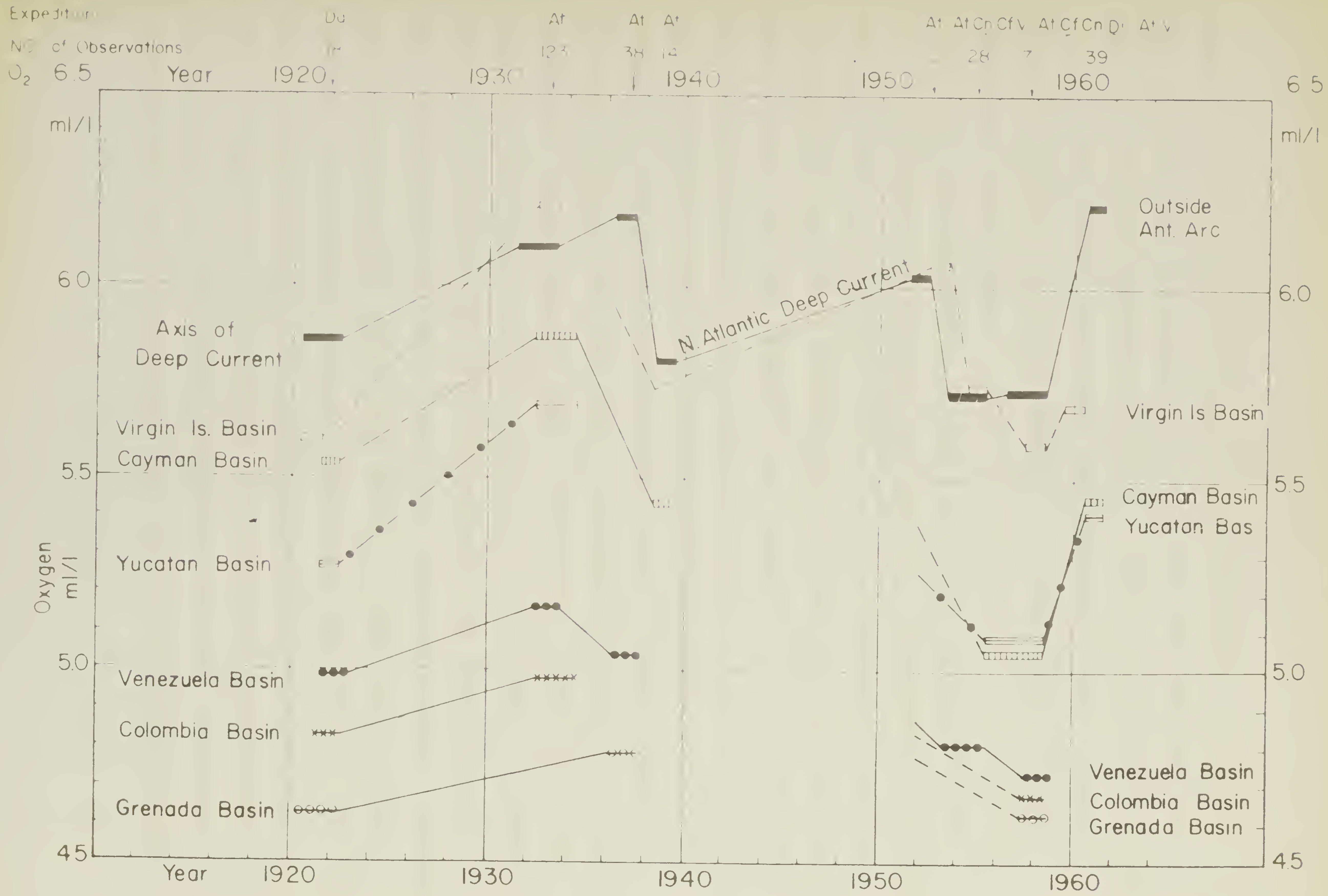
FIGURE 1 2



Distribution of Oxygen in the Core of the Intermediate O_2 Maximum (In about 2000m)
1954-1958
For Explanation of Symbols see Table I
O_2 Contours
Deep Current
Advection-overflo
<1000m
>6.0 ml/l

FIGURE 1 3

within the curved core between 1800 and 2400 meters. Generally they disclose the same pattern of circulation and overflow, but only in a qualitative manner. By the hatching of the areas greater than 6.0 ml/l and by the arrows, they give a clear impression of the quite different absolute values with regard to the renewal of the North Atlantic Deep Water in these two periods. For a better comparison, the mean values for each basin and observation period are calculated and represented in Figure 14. The standard deviations from the average are in most basins less than ±0.15 ml/l or 3% in any single period. Three maxima (1933-37, 1952 and 1961) and three minima (1921, 1939 and 1954-58) in the oxygen content are observed by the various expeditions in the seven basins. They are most pronounced and the highest in the best-ventilated basins outside and partly also inside the Antillean Arc in the following sequence: (1) Main tongue of the deep current outside, (2) Virgin Islands basin, (3) Cayman basin, and (4) Yucatan basin. Within the other interior basins, i.e., (5) the Venezuela, (6) Colombia, (7) Grenada basins, the oxygen values are remarkably low in that order, and the variations are smoothed, permitting some qualitative conclusions on the greater age of their water masses. After these results, it appears that any hope to use such variations as a quantitative time scale of the renewal of the Caribbean deep waters (Worthington, 1955) must be given up. In summary: the variations in the oxygen determinations of the various expeditions since 1921 are partly genuine unperiodic fluctuations, but partly (particularly between



Variations of the average Oxygen Content found by Various Expeditions (1921 – 1961) in the Core Layer of the North Atlantic Deep Water (Upper Oxygen Maximum) within the Basins of the Antillean-Caribbean Region FIGURE 1 4

1954 and 1958) also a consequence of the analytic difficulties. The important question remaining is to what extent the latter have contributed to the observed variations. This can only be discussed in detail when the report of the International Oxygen Commission by Dr. Carritt on the limits of error in former oxygen determinations will be available.

The oxygen section through the Windward Passage and the Cayman-Yucatan basins (Figure 15) shows the vertical distribution of oxygen between 1000 and 8000 meters along the axis of the North Atlantic Deep Current. This section is valid for the period 1933-34, where, in the North Atlantic Deep Water and its overflow, high values were observed. In this case there are in the Cayman basin two intermediate core layers of more than 6.0 ml/l: one in a far-reaching current between 2200 and 3000 meters, the second and less important in about 5000 meters as an occasional and not far-reaching overflow by water masses of higher density. A slight rise in the great layer of North Atlantic Deep Water (setting south) outside the Windward Passage must cause an immediate inclined advection of highly-saturated water masses along the inner slope of the threshold down to the depths of 5000 meters where they meet their original density. A similar but smaller scale counterpart is given for 1933 in the section through the Jamaica Passage and the central regions of the Colombia basin (Figure 16). The southward overflow produces in the latter two weak advective processes in water masses of 5.25 to 5.50 ml/l: one far-reaching between 1400 and 1800 meters, and a second but limited one in approximately 2500 meters. The last

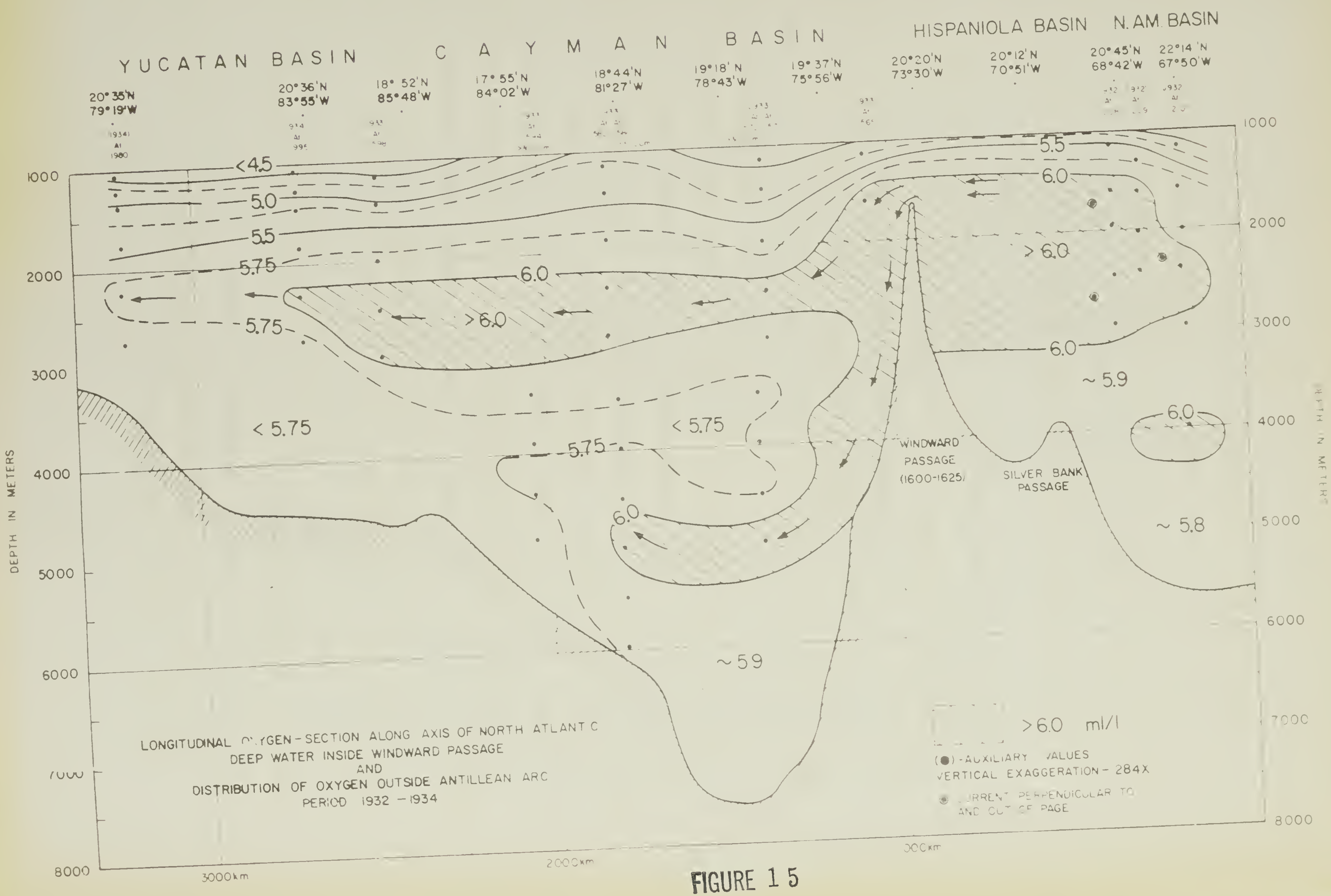
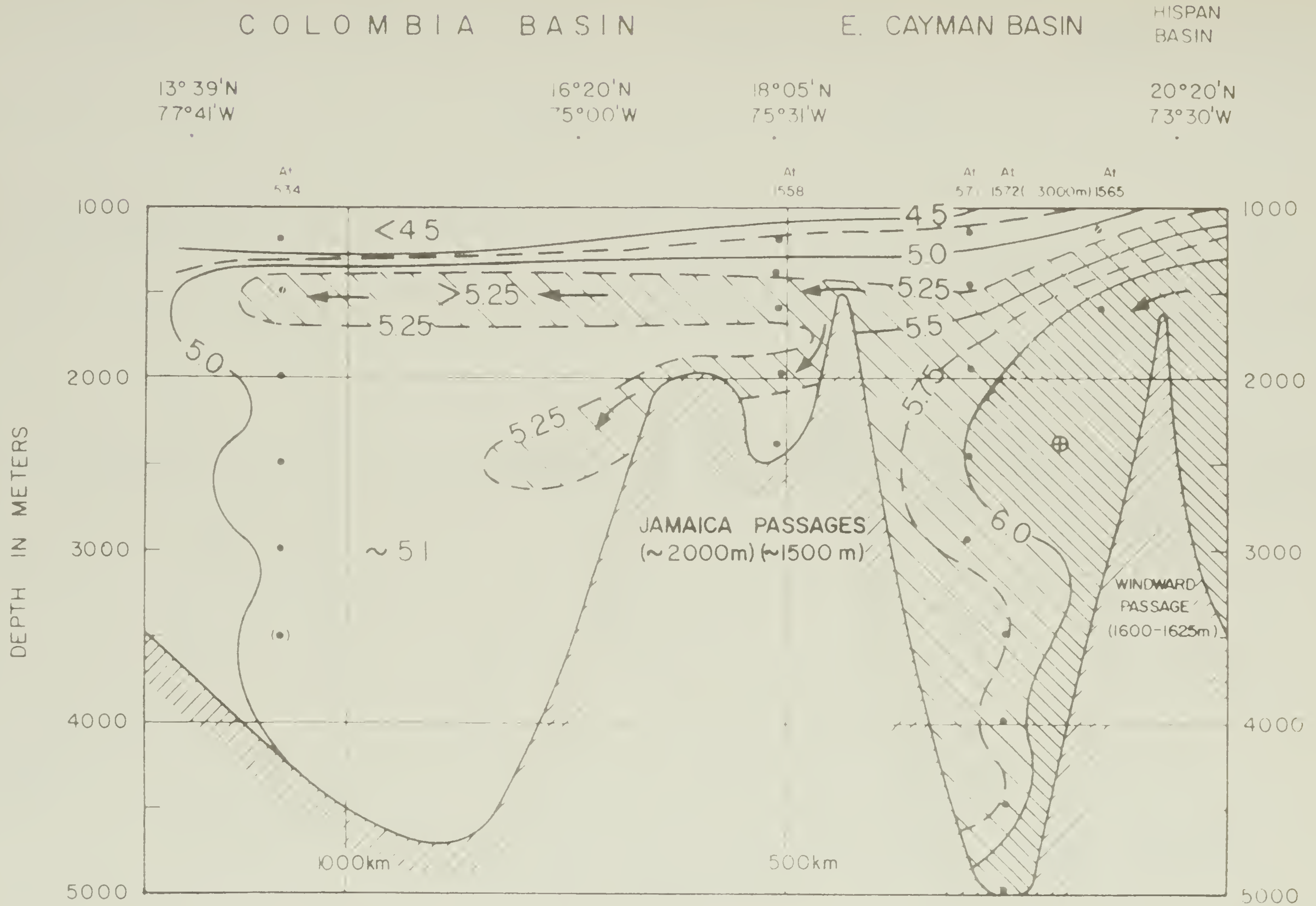

YUCATAN BASIN
CAYMAN BASIN
HISPANIOLA BASIN
N. AM. BASIN
20°35'N 79°19'W
20°36'N 83°55'W
18°52'N 85°48'W
17°55'N 84°02'W
18°44'N 81°27'W
19°18'N 78°43'W
19°37'N 75°56'W
20°20'N 73°30'W
20°12'N 70°51'W
20°45'N 68°42'W
22°14'N 67°50'W
DEPTH IN METERS
<4.5
5.0
5.5
5.75
6.0
>6.0
< 5.75
~5.9
~5.8
WINDWARD PASSAGE (1600-1625)
SILVER BANK PASSAGE
3000km
2000km
>6.0 ml/l
(●) - AUXILIARY VALUES
VERTICAL EXAGGERATION - 284X
LONGITUDINAL OXYGEN-SECTION ALONG AXIS OF NORTH ATLANTIC
DEEP WATER INSIDE WINDWARD PASSAGE
AND
DISTRIBUTION OF OXYGEN OUTSIDE ANTILLEAN ARC
PERIOD 1932 - 1934

FIGURE 15



OXYGEN SECTION THROUGH JAMAICA AND WINDWARD PASSAGES AND THE CENTRAL COLUMBIA AND THE EAST CAYMAN BASINS (1933)

5.25-6.0

6.0 ml/l

⊕ Perpendicular Current Directed into the Paper

Vertical Exaggeration 189X

(●) Auxilliary Values

FIGURE 16

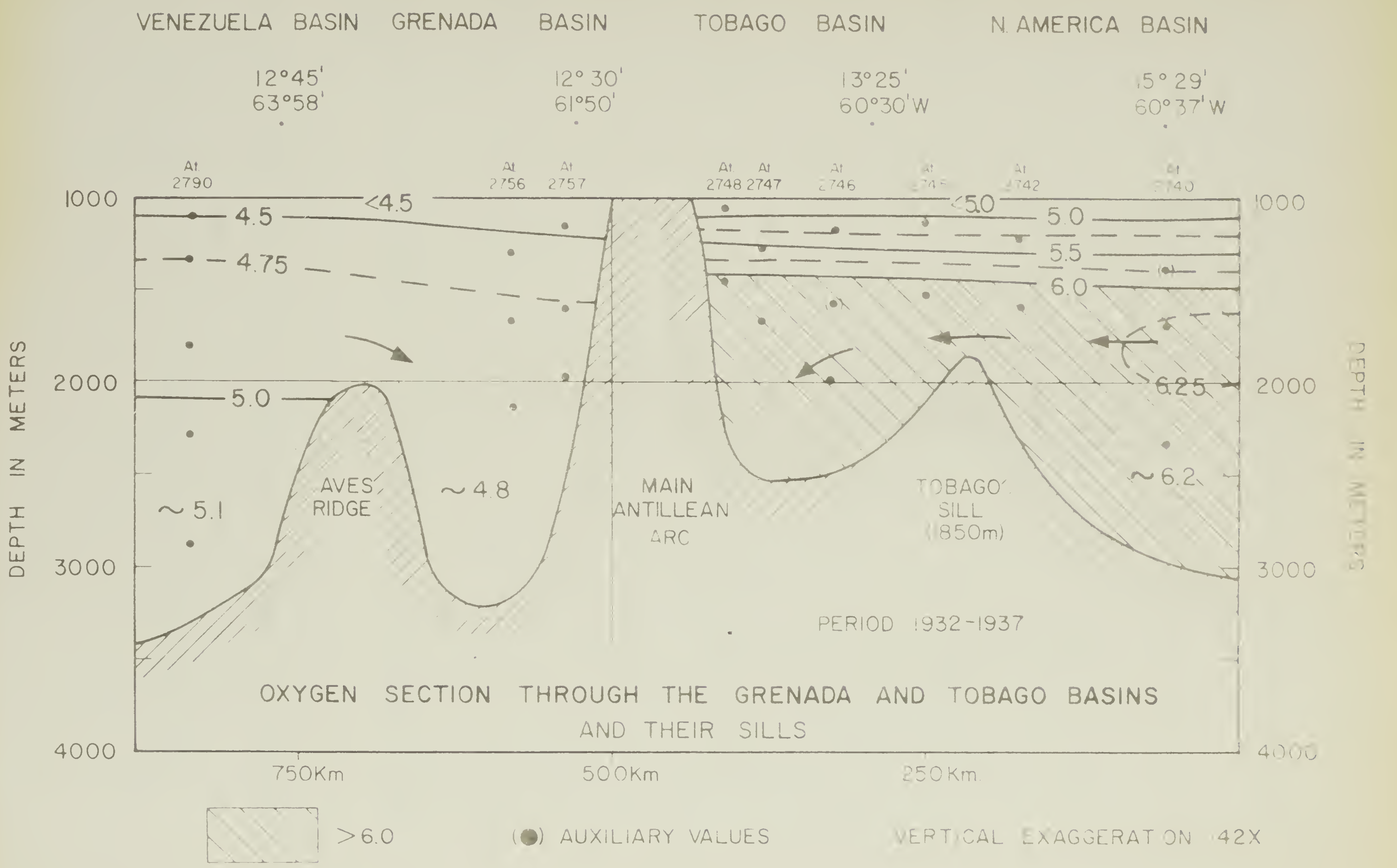
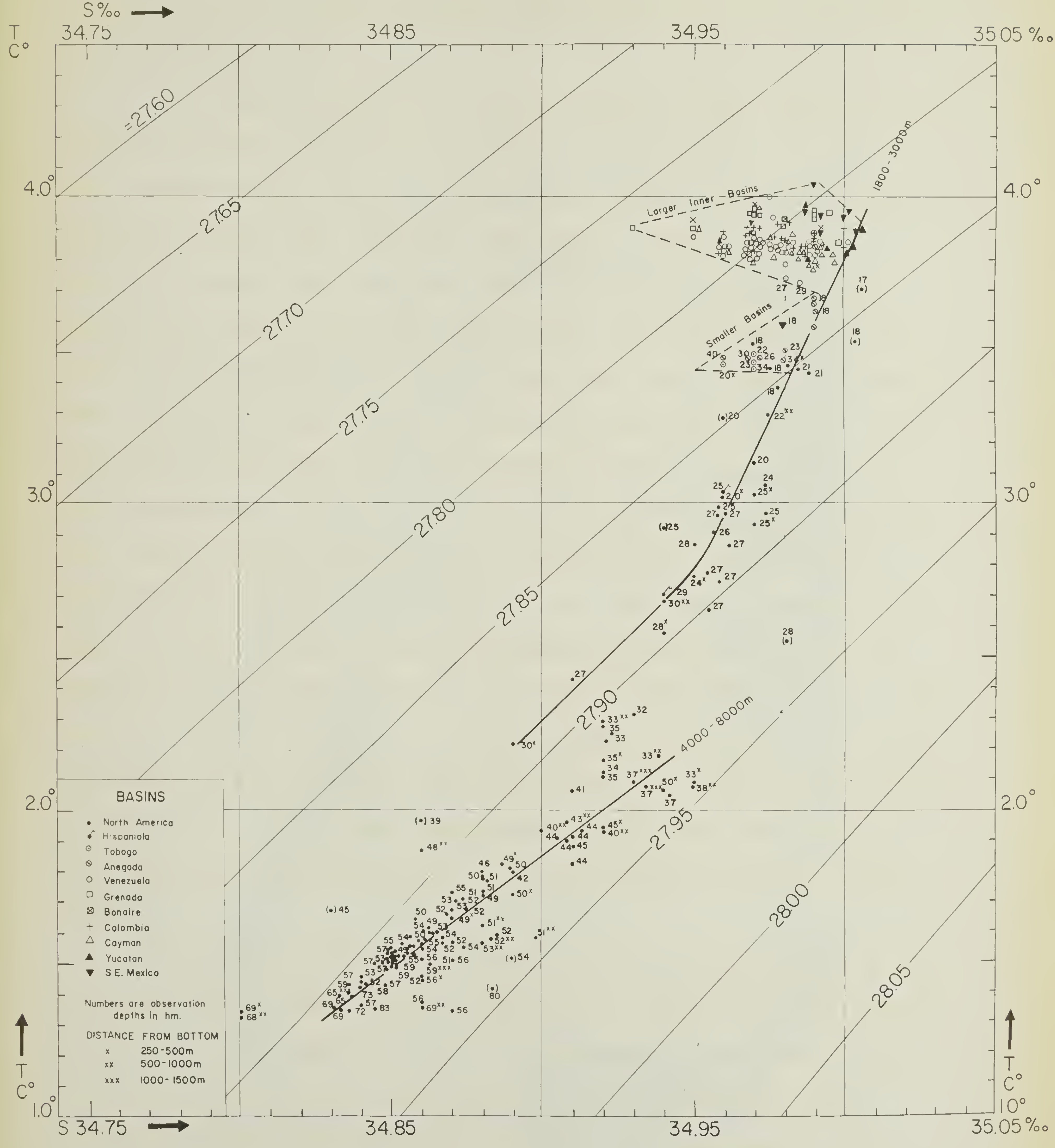

VENEZUELA BASIN
GRENADA BASIN
TOBAGO BASIN
N. AMERICA BASIN
12°45'
63°58'
12° 30'
61°50'
13°25'
60°30'W
15° 29'
60°37'W
At 2790
At 2756
At 2757
At 2748
At 2747
At 2746
At 2742
DEPTH IN METERS
1000
2000
3000
4000
<4.5
4.5
4.75
5.0
~5.1
~4.8
AVES RIDGE
MAIN ANTILLEAN ARC
<5.0
5.0
5.5
6.0
6.25
~6.2
TOBAGO SILL (850m)
PERIOD 1932-1937
OXYGEN SECTION THROUGH THE GRENADA AND TOBAGO BASINS
AND THEIR SILLS
750Km
500Km
250Km
>6.0
(●) AUXILIARY VALUES
VERTICAL EXAGGERATION 42X

FIGURE 17

oxygen section (Figure 17) shows the overflow over the Aves ridge and the Tobago sill.

The circulation of the bottom waters is best characterized by the potential temperature, salinity and potential density of the nearest bottom layer. In the Mediterranean Sea, the author (1960-61) found slow advective processes. In the Antillean-Caribbean basins the circulation of the bottom waters is more complicated and on the whole more rapid. In some basins it has a current-like pattern. For this study about 400 stations of twenty-five research vessels in the period 1921-1961 are utilized. They are first tested on a T/S diagram (Figure 18). Two normal curves are constructed. One is valid for bottom depths between 4000 and 8000 meters, which represents the conditions in the Antarctic Bottom Water outside the Antillean Arc. The other corresponds to the conditions in the Caribbean Bottom Water which is formed by overflow of the North Atlantic Deep Water (1800-4000 meters). The spread in the two clouds of points is remarkably small. Most observations show deviations between ± 0.01 and ± 0.02 in temperature and salinity. All bottom observations within the inner basins fall into the two triangles on the left side of the upper normal curve.

The next map (Figure 19) represents the distribution of the potential bottom temperature in the basins deeper than 2000 meters. It shows a close dependency on the bathymetric conditions. Outside the Antillean Arc, two branches of the relatively swift Antarctic Bottom Current, with velocities of approximately ten



S‰ →
T C°
34.75
34.85
34.95
35.05 ‰
σ=27.60
27.65
27.70
27.75
27.80
27.85
27.90
27.95
28.00
28.05
Larger Inner Basins
Smaller Basins
1800 - 3000m
4000 - 8000m
4.0°
3.0°
2.0°
1.0°
BASINS
North America
Hispaniola
Tobago
Anegada
Venezuela
Grenada
Bonaire
Colombia
Cayman
Yucatan
S.E. Mexico
Numbers are observation depths in hm.
DISTANCE FROM BOTTOM
x 250-500m
xx 500-1000m
xxx 1000-1500m
S 34.75

FIGURE 18


Distribution of Potential Temperature in the Near Bottom Waters of the Deep Basins (>2000m) in the Caribbean-Antillean Region
Contour Lines (generalized) for 1000m 2000m 3000m, 4000m 6000m 8000m, and in special areas 5000m and 5500m given in hectometers
Isotherms of Potential Bottom Temperature
Auxiliary isotherms
Axis of Bottom Current
Axis of Advection in the Bottom Water
< 2000m
< 1.60°
For Explanation of Symbols see Table 1
Outer Ridge
1.62 – 1.80
1.46 – .49
3.77 – 3.79
3.94 – .98
85°
80°
75°
70°
65°
60°
25°
20°
15°
10°

FIGURE 1 9

centimeters per second (Wust, 1957) and with temperatures of less than 1.60°, flow to the northwest, separated by the Outer Ridge. The latter shows a gap and overflow north of Puerto Rico. Inside the Antillean Arc a similar swift bottom current exists in the channel-like deep Cayman basin in continuation of the strong overflow through the Windward Passage. The overflow through the Virgin Islands Passage does not produce stream-like pattern at the bottom of the expanding Venezuela basin. Here, as well as in the Colombia basin, sluggish advective processes are predominant in the bottom layer. A map of the bottom salinity confirms for the whole area the results derived from the potential bottom temperature.

A fundamental question is still incompletely answered: What are the deciding sill depths in the main passages between the basins of the Antillean-Caribbean region? This question can best be solved with the help of vertical sections of potential temperature as long as sufficiently close-meshed bathograms are unavailable. The latter is still the case, in most passages. The first successful approaches by this method, based on a relatively small number of stations, have been made by Dietrich (1937 and 1939). The following new sections of potential temperatures, based on five to ten times as many observations, have permitted us to go more deeply into detail. The first section follows the axis of the Antarctic Bottom Current outside the Antillean Arc to the northwest, turns over the Silver Bank Ridge and the Windward Passage to the west along the axis of the bottom current in the Cayman basin and ends after a new turn to the northeast in the


Positions of Stations
Along the Vertical
tp and O2 Sections
A,C,E-tp Sections
B,D,F-O2 Sections
<1000m

FIGURE 2 0

Yucatan basin (Figure 20). The main longitudinal section shows the rapid and far-reaching overflow of water masses of 3.75° to 3.80° through the Windward Passage, which fill all the depths of the Cayman trench between 4000 and 8000 meters and reach in their last traces to the center of the Yucatan basin. The sill depth of the Windward Passage found by this method is in agreement with Dietrich's result (1937) of 1600 to 1625 meters (Figure 21). The other section goes through the Anegada Passage and Virgin Islands Passage to the northwest Venezuela basin (Figure 22). This second section gives two sill depths of 1950 and 2300 meters in the Anegada Passage and a sill depth of approximately 1750 meters in the Virgin Islands Passage. In spite of the fact that the latter value represents the deepest connection between the Atlantic Ocean and the Central American basins, its overflowis of minor importance for the renewal of the Antillean-Caribbean Bottom Water masses as compared with that of the shallower, but wider Windward Passage. The Anegada-Virgin Passage overflow forms only a relatively thin bottom layer of less than 3.80° in the Venezuela basin. Finally the potential temperature section through the South Aves and Dominica Passages demonstrates the importance of the first for the renewal of the bottom waters in the Grenada basin (Figure 23). Table 1 gives a summary of the recent determinations of the width and the deepest depth of the main passages. The most probable numbers of the sill depths are underlined.

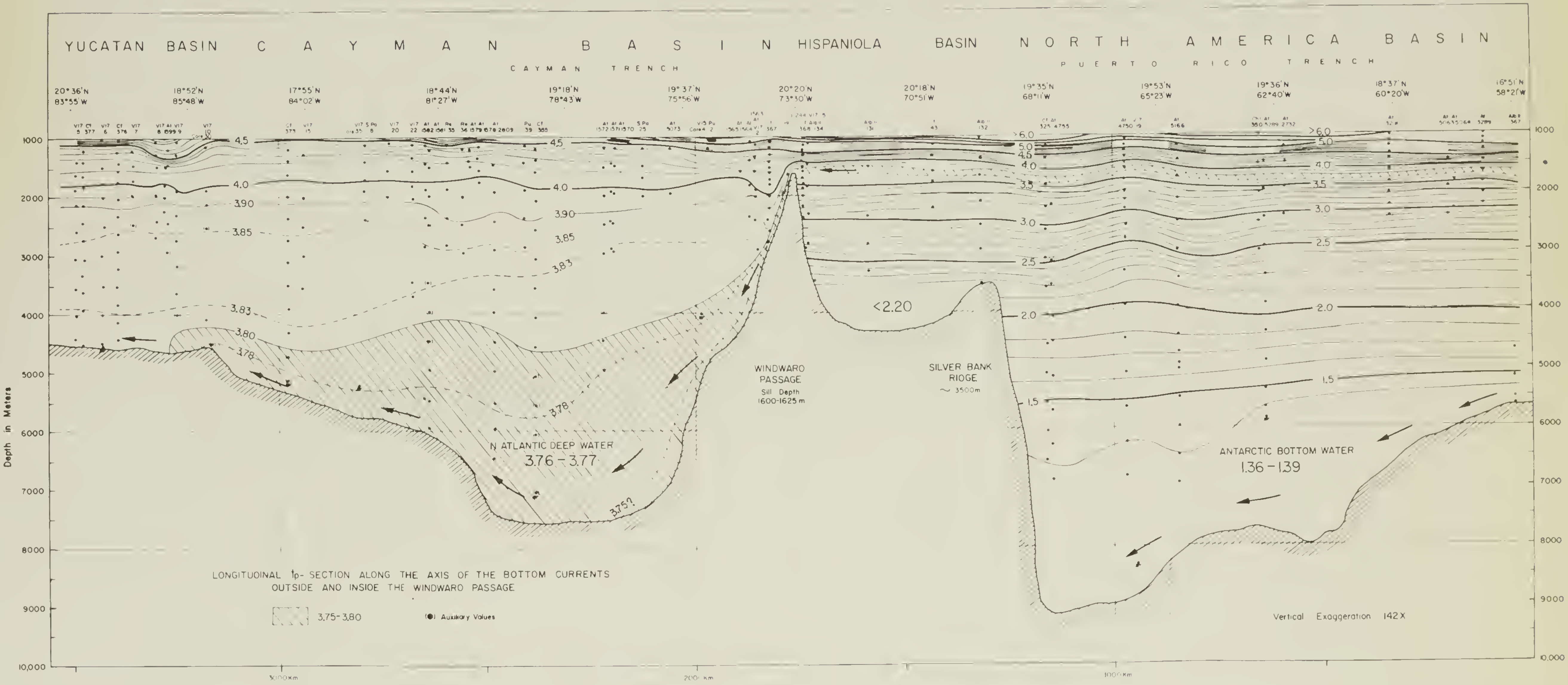

YUCATAN BASIN
CAYMAN BASIN
CAYMAN TRENCH
HISPANIOLA BASIN
NORTH AMERICA BASIN
PUERTO RICO TRENCH
20°36'N 83°55'W
18°52'N 85°48'W
17°55'N 84°02'W
18°44'N 81°27'W
19°18'N 78°43'W
19°37'N 75°56'W
20°20'N 73°30'W
20°18'N 70°51'W
19°35'N 68°11'W
19°53'N 65°23'W
19°36'N 62°40'W
18°37'N 60°20'W
16°51'N 58°21'W
<2.20
WINDWARD PASSAGE
Sill Depth 1600-1625 m
SILVER BANK RIDGE
~ 3500m
N ATLANTIC DEEP WATER
3.76 - 3.77
ANTARCTIC BOTTOM WATER
1.36 - 1.39
Depth in Meters
LONGITUDINAL t_p- SECTION ALONG THE AXIS OF THE BOTTOM CURRENTS OUTSIDE AND INSIDE THE WINDWARD PASSAGE
3.75-3.80
(●) Auxiliary Values
Vertical Exaggeration 142 X

FIGURE 2 1

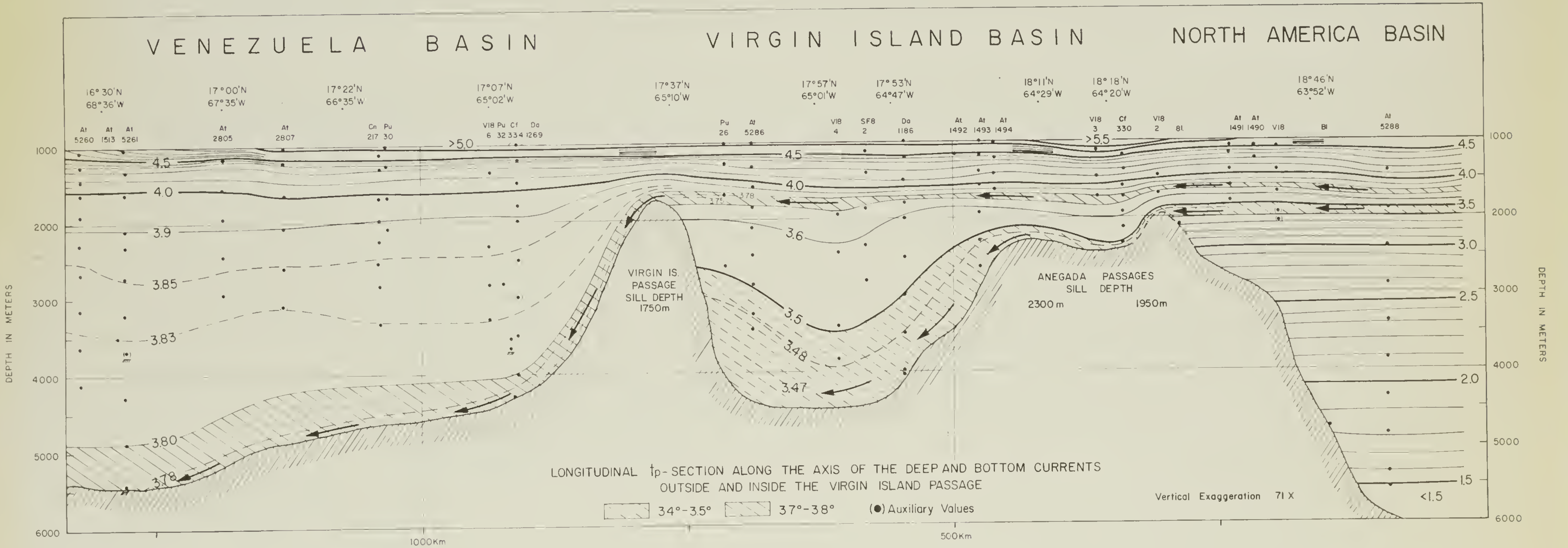

VENEZUELA BASIN
VIRGIN ISLAND BASIN
NORTH AMERICA BASIN
DEPTH IN METERS
VIRGIN IS. PASSAGE SILL DEPTH 1750m
ANEGADA PASSAGES SILL DEPTH
2300 m
1950m
LONGITUDINAL tp-SECTION ALONG THE AXIS OF THE DEEP AND BOTTOM CURRENTS OUTSIDE AND INSIDE THE VIRGIN ISLAND PASSAGE
34°-35°
37°-38°
(●) Auxiliary Values
Vertical Exaggeration 71 X
1000Km
500Km

FIGURE 22

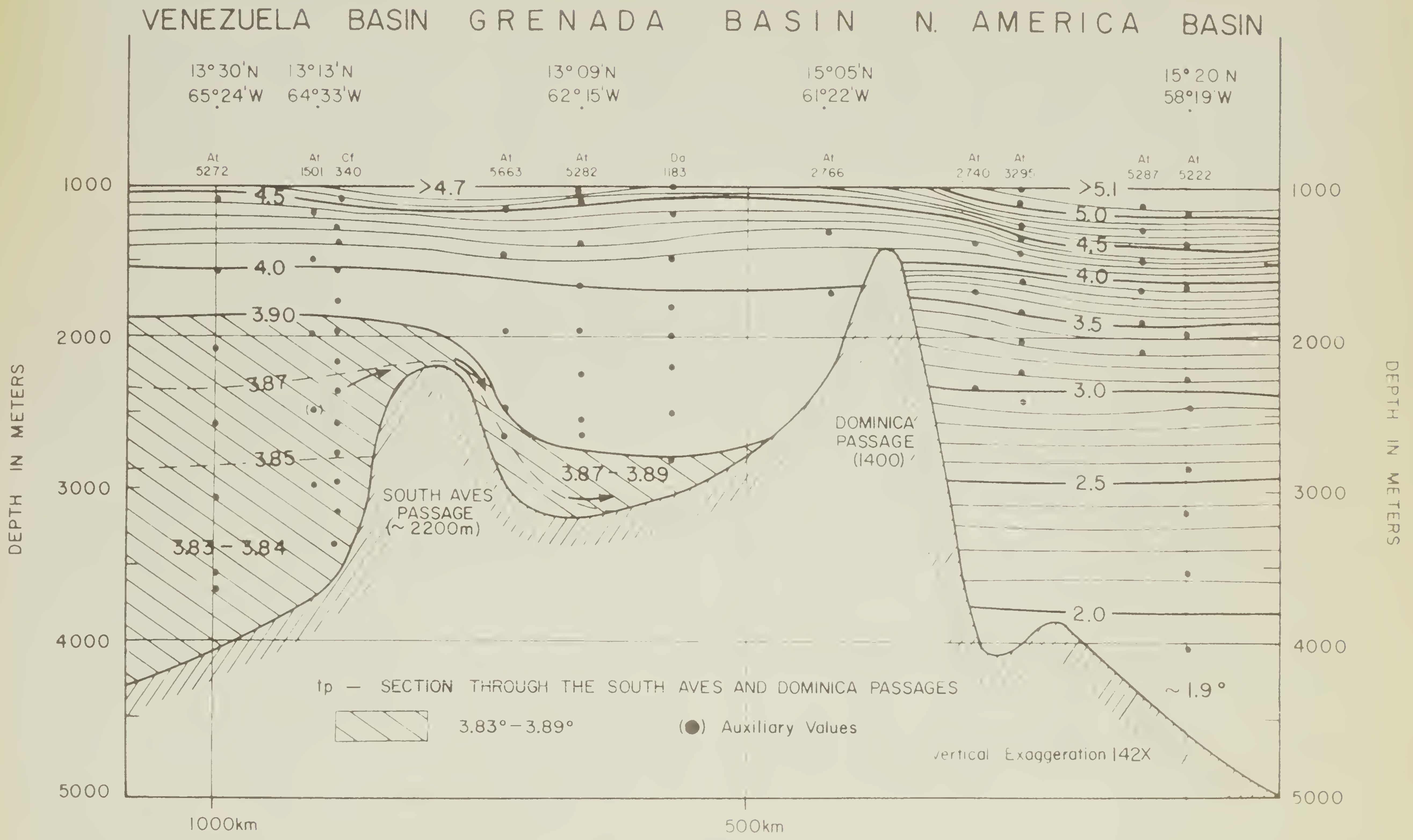

VENEZUELA BASIN
GRENADA BASIN
N. AMERICA BASIN
13°30'N 65°24'W
13°13'N 64°33'W
13°09'N 62°15'W
15°05'N 61°22'W
15°20'N 58°19'W
At 5272
At 1501
Cf 340
At 5663
At 5282
Da 1183
At 2766
At 2740
At 3295
At 5287
At 5222
DEPTH IN METERS
1000
2000
3000
4000
5000
>4.7
4.5
4.0
3.90
3.87
3.85
3.83 – 3.84
3.87 – 3.89
>5.1
5.0
4.5
4.0
3.5
3.0
2.5
2.0
~1.9°
SOUTH AVES PASSAGE (~2200m)
DOMINICA PASSAGE (1400)
tp — SECTION THROUGH THE SOUTH AVES AND DOMINICA PASSAGES
3.83° – 3.89°
(●) Auxiliary Values
Vertical Exaggeration 142X
1000km
500km

FIGURE 23

TABLE 1

SILL DEPTHS BETWEEN THE BASINS OF THE ANTILLEAN-CARIBBEAN REGION

PASSAGES Name	Width at 1500m	SILL DEPTHS IN TRUE M By Bathogram	By tp and O_2 Sections[3]
Windward Passage	12 miles	1650[1]	1600-1625
Virgin Islands Passage	8 miles	1960[2]	1725-1775
Anegada Passage	8 miles	2208[2]	North ~1950 South ~2300
Dominica Passage	-	1372[2]	~ 1400
Jamaica Passage	20 miles (at 1000m)	1500[1]	1450-1500
South Aves Passage	-	-	~ 2200

1 After Heezen-Johnson-Allen 1961

2 After Frassetto-Northrop 1957

3 After Wüst-Gordon 1962

The most probable values are underlined.

All the more or less rapid incoming circulation of the low temperature deep and bottom water masses must, in the face of downward diffusion of heat from above, be balanced by a very slow upward component of velocity over most of the Antillean-Caribbean Sea in order to maintain the continuity. Stommel-Arons (1958 and 1960) and recently Wyrtki (1961) pointed out the same idea for the thermohaline vertical circulation of the world ocean. For the

lower latitudes of all oceans these authors have calculated an average for the upward velocities in the order of magnitude of $1 - 3 \times 10^{-5}$ cm/sec. In connection with the dynamic computations of the volume transports, we will try to calculate the vertical components within the Antillean-Caribbean basins. Such computations will complete, in a quantitative manner, the picture of the deep circulation given in this abstract mainly with the help of the core method.

This study has been largely supported by the United States Atomic Energy Commission under contract AT (30-1) 2663. The author is grateful to the Ford Foundation for supporting the Visiting Professorship in Oceanography at Columbia University.

REFERENCES

Defant, A., Ausbreitungs-und Vermischungs vorgänge im antarktischen Bodenstrom und im subantarktischen Zwischen wasser; Deutsche Atlantische Expedition "Meteor," Band VI, 2, 2 lief, 1936.

Defant, A., Die absolute Topographic des physikalischen Meeres-niveaus und der Druckflächen, so wie die Wasserbewegungen Atl. Ozean; Deutsche Atlantische Expedition, "Meteor," Band VI, 2, 5, Lief, 1941.

Defant, A., Physical Oceanography, Pergamon Press, Ltd., New York. Vol. 1, 1962.

Dietrich, G., Fragen der Grossformen und der Herkunft des Tiefen-wassers im Amerikanischen Mittelmeer; Ann. d. Hydr. u. Marit. Met., 345, 1937.

Dietrich, G., Das Amerikanische Mittelmeer. Ein meereskundlicher Uberblick; Zeitschr. Ges. f. Erdkunde Berlin, 108-130, 1939.

Dietrich, G., Allgemeine Meereskunde; Gebrüder Borntraeger, Berlin, 1957.

Frassetto, R. and J. Northrop, Virgin Islands bathymetric survey; Deep-Sea Research, 4, 138-145, 1957.

Fuglister, F. C., Atlantic Ocean atlas of temperature and salinity profiles and data from the International Geophysical Year, 1957-1958, Woods Hole Oceanographic Institution, Woods Hole, Mass., 1960.

Gerard, R., M. G. Langseth and M. Ewing, Thermal gradient measure-ments in the water and bottom sediment of the Western Atlantic; Jour. Geophysical Research, 67, 785-803, 1962.

Heezen, B. C., G. L. Johnson and R. C. Allen, Geological and oceanographic aspects of submarine cable engineering; Tech. Report, Lamont Geological Obsvy.(Prepared for Bell Labs.) 1961.

Krümmel, O., Handbuch der Ozeanographie Bd. I. Stuttgart, 1907.

Model, F., Pillsbury's Strommessungen und der Wasserhaushalt des Amerikanischen Mittelmeeres Deutsch. Hydrogr. Zeischt 3, 1950.

Montgomery, R. H., Ein Versuch den vertikalen und seitlichen Austausch in der Tiefe der Sprungschichte im Äquatorialen Atlantischen Ozean zu bestimmen; Annalen der Hydrographie u. Marit. Met., Berlin, 1939.

Parr, A. E., A contribution to the hydrography of the Caribbean and Cayman Seas; Bull. Bingham Oceanogr. Coll., Vol. V., 1-110, 1937.

Richards, F. A., Oxygen in the ocean; Geol. Soc. America, Memoir 67, 1, 185-238, 1957.

Richards, F. A., Some current aspects of chemical oceanography; Physics and Chemistry of the Earth, Vol. 2, Pergamon Press, London, 1957.

Stommel, H. and A. B. Arons, On the abyssal circulation; Deep-Sea Research, 6, 140-154, 219-233, 1960.

Sverdrup, H. U., M. W. Johnson and R. H. Fleming, The oceans, their physics, chemistry and general biology; Prentice Hall, New York, 1942.

Swallow, J. C. and L. V. Worthington, An observation of a deep counter current in the western North Atlantic; Deep-Sea Research, 8, 1-19, 1961.

Wattenberg, H., Die Verteilung des Sauerstoffs im Atlantischen Ozean; Deutsche Atlantische Expedition, "Meteor," Werk, Vol. 9, Lief 1, Berlin, 1938.

Worthington, L. V., A new theory of Caribbean bottom-water formation; Deep-Sea Research, 3, 82-87, 1955.

Wüst, G., Schichtung und Zirkulation des Atlantischen Ozeans die Stratosphäre; Deutsche Atlantische Expedition "Meteor", Vol. VI, 1, Berlin, 1936.

Wüst, G., Stromgeschwindigkeiten und Strommengen in den Tiefen des Atlantischen Ozeans: Deutsche Atlantische Expedition "Meteor" Vol. VI, 2, 261-420, Berlin, 1957.

Wüst, G., Die Tiefenzirkulation des Mittellandischen Meeres in den Kernschichten des Zwischen und Tiefenwassers; Deutsche Hydrograph. Zeitschr. 13, 3, 105-131, 1960.

Wüst, G., Das Bodenwasser und die Vertikalzirkulation des Mittelandischen Meeres; Deutsche Hydrograph. Zeitschr. 14, 3, 81-92, 1961.

Wüst, G., On the vertical circulation of the Mediterranean Sea; Journal Geophysical Research, Vol. 66, 10, 3261-3271, 1961.

Wyrtki, K., The thermohaline circulation in relation to the general circulation in the oceans; Deep-Sea Research 8, 1, 39-64, 1961.

Wyrtki, K., The oxygen minima in relation to oceanic circulation; Deep-Sea Research, 9, 11-28, 1962.